Tracers in MOM6

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Active and passive tracers

Active tracers

- Affect momentum equations through the equation of state
- Typically: conservative temperature and absolute salinity

Quasi-active tracers (handwavey definition)

- Influences fluxes of an active tracer
- Example: Chlorophyll affects absorption of shortwave radiation in a water column

Passive tracers

- No effect on momentum or the equation of state
- Most biogeochemistry (oxygen, nutrients, phytoplankton), radioactive isotopes, transient tracers, ideal age, dyes

Building a tracer tendency budget

- Recall: a specific (x,y,z) point represents a finite volume with constant area and time-varying thickness
- Concentration tendency not necessarily conserved

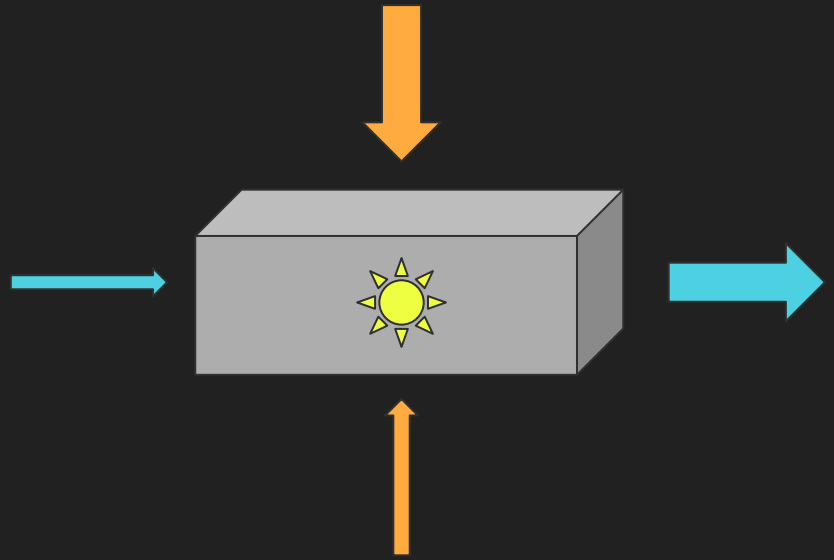
$$\frac{\partial}{\partial t}\phi$$

- Tracer content is conserved

$$\frac{\partial}{\partial t}\phi h$$

- Also applies to z^* coordinate due to stretching by barotropic mode

$$\frac{\partial}{\partial t}\phi h = \frac{1}{\Delta t}\left(\phi_{t+1}h_{t+1} - \phi_t h_t\right) = F_{j+1} - F_j + \text{internal}$$



Heat budget in MOM6 (ALE mode)

Process	3D diagnostic?	Column integral 0?
Horizontal advection (resolved + mesoscale + submesoscale)	Yes	No
Neutral diffusion	Yes	No
Lateral boundary diffusion	Yes	No
Vertical transport (ALE regridding/remapping)	Yes	Yes
Vertical diffusion (aggregated)	Yes	Yes
Surface boundary fluxes (aggregated and individual) Gustavo's Notebook for conventions and components	Yes	No
Frazil formation	Yes	No
Geothermal (internal) heating	Yes	No

Recent heat budget auditors: Gustavo Marques, Graeme Macgilchrist, and Andrew Shao

Tracer budgets close in diagnostic coordinates

- MOM6 diagnostic manager can output on any of the vertical coordinates
  - Conservative temperature coordinate is in development with Graeme Macgilchrist
  - Other coordinates? Oxygen? Age?
- Heat budget does close in the OM4 configuration (and probably others) in native, z^*, and isopycnal
- Transformations are done at the timestep of the model
- Note: This can become a fairly expensive part of the model

MOM6 is particularly well suited for water mass transformation analysis

The MOM6 Tracer Framework

General tracer information

- No distinction made in the algorithm between active and passive tracers
  - If **Temperature** and **Salinity** are specifically needed, use the `thermo_var_ptrs` type usually named `tv`
- Horizontal and vertical processes, and source/sink calculations are called at the frequency specified by `DT_THERM`
  - `DT_THERM` can be an integer multiple of the baroclinic timestep **DT**
- Other than advection and horizontal diffusion, any other updates to the tracer must be done by the tracer's module
  - **This includes vertical diffusion!**
- MOM6 has **no tendency arrays** (c.f. MOM5 or NEMO)
  - **Tracer modules are responsible for their own timestepping!**

MOM6 tracer framework overview

MOM tracer registry

- Keeps track of ***all*** tracers (active + passive)
- Defines the *tracer* type (view on readthedocs)
- Any registered tracers will be advected, diffused, and remapped
    - All associated diagnostics can be requested

MOM tracer flow control

- Serves as the main driver routine for each tracer module

Describing the basic ‘tracer flow control’

1. Register tracers
    a. Configure from MOM_input
    b. After call, tracer will be advected and diffused also added to the restart
2. Perform initialization (either from restart or cold start)
3. Time loop:
    a. **`call_tracer_column_fns:`** Do any and all vertical processes
        i. Concentration/dilution due to freshwater fluxes (ALE only)
        ii. Apply vertical mixing, flux boundary conditions, vertical velocities
        iii. Update concentrations from internal sources and sinks
    b. **`call_tracer_stocks:`**
        i. Calculate and store global inventories of tracers
4. Finalization
    a. Free any allocated memory

Example: boundary impulse tracer

- Numerical analogue of calculating a Green's function
  - Surface tracer concentration set to 1 for a period of time. Afterwards, always set to 0

register_boundary_impulse_tracer (tracer package configuration and definition):

```
call get_param(param_file, mdl, "IMPULSE_SOURCE_TIME",
CS%remaining_source_time, &
                "Length of time for the boundary tracer to be injected "//&
                "into the mixed layer. After this time has elapsed, the "//&
                "surface becomes a sink for the boundary impulse tracer.", &
                default=31536000.0)
call get_param(param_file, mdl, "TRACERS_MAY_REINIT", CS%tracers_may_reinit, &
                "If true, tracers may go through the initialization code "//&
                "if they are not found in the restart files.  Otherwise "//&
                "it is a fatal error if the tracers are not found in the "//&
                "restart files of a restarted run.", default=.false.)

allocate(CS%tr(isd:ied,jsd:jed,nz,CS%ntr)) ; CS%tr(:,:,:,:) = 0.0

CS%tr_desc(m) = var_desc(trim("boundary_impulse"), "kg kg-1", &
        "Boundary impulse tracer", caller=mdl)
        if (GV%Boussinesq) then ; flux_units = "kg kg-1 m3 s-1"
                else ; flux_units = "kg s-1" ; endif
tr_ptr => CS%tr(:,:,:,m)
call query_vardesc(CS%tr_desc(m), name=var_name, &
        caller="register_boundary_impulse_tracer")
```

(register tracer with registry and restart fields)

```
! Register the tracer for horizontal advection, diffusion, and restarts.
call register_tracer(tr_ptr, tr_Reg, param_file, HI, GV,
tr_desc=CS%tr_desc(m), &
                        registry_diags=.true., flux_units=flux_units, &
                        restart_CS=restart_CS,

! Register remaining source time as a restart field
rem_time_ptr => CS%remaining_source_time
call register_restart_field(rem_time_ptr, "bir_remain_time", &
                            .not. CS%tracers_may_reinit, restart_CS, &
                            "Remaining time to apply BIR source", "s")
```

Example: Initialization and physical processes

```
Initialize_boundary_impulse_tracer (set initial conditions or read from restart)
if ((.not.restart) .or. (.not. &
    query_initialized(CS%tr(:,:,:,m), name, CS%restart_CSp))) then
  do k=1,CS%nkml ; do j=jsd,jed ; do i=isd,ied
    CS%tr(i,j,k,m) = 1.0
  enddo ; enddo ; enddo
endif

boundary_impulse_tracer_column_physics:
! This uses applyTracerBoundaryFluxesInOut, usually in ALE mode
if (present(evap_CFL_limit) .and. present(minimum_forcing_depth)) then
  do k=1,nz ;do j=js,je ; do i=is,ie
    h_work(i,j,k) = h_old(i,j,k)
  enddo ; enddo ; enddo

  call applyTracerBoundaryFluxesInOut(G, GV, CS%tr(:,:,:,1), dt, fluxes, h_work, &
                                      evap_CFL_limit, minimum_forcing_depth)
  call tracer_vertdiff(h_work, ea, eb, dt, CS%tr(:,:,:,1), G, GV)

else
  call tracer_vertdiff(h_old, ea, eb, dt, CS%tr(:,:,:,1), G, GV)
endif
```

Note: **ea** and **eb** are entrainment from above or below. For ALE mode, this is only diffusion such that **ea(k)=-eb(k-1)**

tracer_vertdiff also can apply boundary fluxes and vertical sinking using an implicit formulation.

Example: Sources and sinks

```
if (CS%remaining_source_time>0.0) then
  do k=1,CS%nkml ; do j=js,je ; do i=is,ie
    CS%tr(i,j,k,m) = 1.0
  enddo ; enddo ; enddo
  CS%remaining_source_time = CS%remaining_source_time - &
     US%T_to_s*dt
else
  do k=1,CS%nkml ; do j=js,je ; do i=is,ie
    CS%tr(i,j,k,m) = 0.0
  enddo ; enddo ; enddo
endif
```

Inject the tracer at the surface ‘mixed layers’. If in ALE mode, this is only at the first layer

Remove all tracer at the surface by resetting any concentrations to 0.

Adding/using your own tracers

- Recommendation: Follow an existing tracer package
  - Most of the time only `MOM_tracer_flow_control.F90` needs to be modified
- Other useful tracer packages:

MOM_OCMIP2_CFC	CFC-11 and CFC-12; passes information to/from GFDL coupler
oil_tracer	Inject tracers near the bottom; potentially do exponential decay
ideal_age_example	Age-like tracers (including ideal age)
dye_example	Inject an arbitrary number of dye tracers within a lat, lon, depth range
pseudo_salt_tracer	‘Should’ reproduce the salinity tracer
MOM_generic_tracer	GFDL biogeochemical model interface (BLING, COBALT, etc.)
MARBL	NCAR BGC itnerface. See Michael Levy’s talk

Who to ask (blame?) about tracers

- Automatic diagnostic checking: Marshall Ward
- Diagnostic remapping: Nic Hannah and Alistair Adcroft
- Closing budgets: Gustavo Marques, Graeme Macgilchrist, Steve Griffies
- Overall framework: Bob Hallberg

I've broken/fixed these many times, so feel free to ask me as well

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Other tracer-related ideas/projects:

- Offline tracer transport: Long orphaned by me and I'm looking for an excuse to work on it again.
- Coarsened advection: Do advection on a coarser grid inline with the rest of MOM6. Particularly important for BGC in eddy-resolving simulations