Working notes on the ocean heat budget in GFDL-ESM2M

Stephen.Griffies@noaa.gov

THE ESM2M SUITE OF SIMULATIONS

A suite of GFDL-ESM2M earth system model simulations has been conducted in which all terms appearing in the heat budget were saved. The following three simulations have been completed:

- root = /archive/Bonnie.Samuels/siena_201305
- 1860 control: `root/ESM2M_pi-control_C2_14jun2013/gfdl.ncrc2-intel-prod-openmp/pp/ocean`
- idealized 2xCO2: `root/ESM2M_pi_C2_2x_CO2_14jun2013/gfdl.ncrc2-intel-prod-openmp/pp/ocean`
- instantaneous 4xCO2: `root/ESM2M_pi_C2_abrupt_4xCO2_14jun2013/gfdl.ncrc2-intel-prod-openmp/pp/ocean`

All heat budget terms were saved at monthly mean and annual mean averages, with 1-100 and 101-200 year time series computed for each term. These notes summarize the various processes contributing to the heat budget, and provide the recipe for analysis of the budget.

Contents

Chapter 1

Ocean heat budgets

Contents

We consider here the physical processes that impact on the ocean heat budget in the GFDL-ESM2M earth system model of Dunne et al. (2012), and present a recipe for diagnosing the heat budget in an ocean grid cell.

1.1 Tracer budget for a grid cell in MOM5

The following semi-discrete equations are the basis for MOM5's tracer budget in the surface, interior, and bottom grid cells

$$\partial_t (C \rho \, \mathrm{d}z) = -\nabla_s \cdot [\rho \, \mathrm{d}z \, (\mathbf{u} \, C + \mathbf{F})] + \Big[\rho \, (w^{(z)} \, C + F^{(z)})\Big]_{s=s_{k=1}} + Q^{(\mathrm{c})}_{\mathrm{advect}} + Q^{(\mathrm{c})}_{\mathrm{non\text{-}advect}} + \mathcal{S}^{(\mathrm{c})} \, \rho \, \mathrm{d}z \tag{1.1a}$$

$$\partial_t (C \rho \, \mathrm{d}z) = -\nabla_s \cdot [\rho \, \mathrm{d}z \, (\mathbf{u} \, C + \mathbf{F})] - [\rho \, (w^{(z)} \, C + F^{(z)})]_{s=s_{k-1}} + [\rho \, (w^{(z)} \, C + F^{(z)})]_{s=s_k} + \mathcal{S}^{(\mathrm{c})} \, \rho \, \mathrm{d}z \tag{1.1b}$$

$$\partial_t (C \rho \, \mathrm{d}z) = -\nabla_s \cdot [\rho \, \mathrm{d}z \, (\mathbf{u} \, C + \mathbf{F})] - \Big[\rho \, (w^{(z)} \, C + F^{(z)})\Big]_{s=s_{kbot-1}} + Q^{(\mathrm{c})}_{(\mathrm{bot})} + \mathcal{S}^{(\mathrm{c})} \, \rho \, \mathrm{d}z. \tag{1.1c}$$

These budgets are formulated as finite volume contributions to the tracer mass per horizontal area (or heat per area) of a grid cell. All grid cells generally have a non-constant thickness and non-constant density (Boussinesq budgets have constant density factor $\rho \to \rho_0$). The lateral convergence operator acting on a flux, $-\nabla_s \cdot \mathbf{J}$, is formulated numerically so that multiplication by the area of a grid cell leads to a difference operator acting on the lateral flux components crossing the tracer grid cell faces. That is, the numerical discretization satisfies Gauss′ Law, as doing so allows us to retain the familiar finite volume budgets within the numerical model. We now detail terms in these equations.

- C is the potential (or conservative) temperature of a grid cell, or the mass of tracer (e.g., salt or DIC) per mass of seawater within the cell (i.e., tracer concentration).
- $\rho\,\mathrm{d}z$ is the mass of seawater per horizontal area in a grid cell, with ρ the *in situ* density and $\mathrm{d}z$ the thickness. ESM2M makes the Boussinesq approximation, so the ρ factor is replaced by a constant reference density
$$\rho_o = 1035 \text{ kg m}^{-3}. \tag{1.2}$$
- The product $C\,\rho\,\mathrm{d}z$ is the mass per unit horizontal area of a grid cell if C is a material tracer such as salinity. Since the horizontal area of the cell is constant in time, we may multiply by the horizontal area to recover a budget for the mass in the cell.
- The product $C\,\rho\,\mathrm{d}z$ is the heat per horizontal area if C is potential or conservative temperature multiplied by the heat capacity. Since the horizontal area of the cell is constant in time, we may multiply by the horizontal area to recover a budget for the heat within the grid cell, in SI units of Joule.
- The generalized level vertical coordinate is denoted by s, and its discrete values s_k determine the vertical grid cell. For ESM2M, we use the vertical coordinate of Stacey et al. (1995) and Adcroft and Campin (2004)
$$s = z^* = H\left(\frac{z-\eta}{H+\eta}\right), \tag{1.3}$$
where z is the geopotential, $z = -H(x,y)$ is the ocean bottom, and $z = \eta(x,y,t)$ is the ocean free surface.
- The horizontal velocity component is $\mathbf{u}$ and vertical component is $w^{(z)}$.
- The horizontal subgrid scale transport is $\rho\,\mathbf{F}$ and vertical component is $\rho\,F^{(z)}$.
- The tracer source is $\mathcal{S}^{(\mathrm{c})}\,\rho\,\mathrm{d}z$. This source is generally nonzero for biogeochemical tracers and zero for heat.
- Tracer flux associated with the boundary water flux is accounted for by the term $Q^{(\mathrm{c})}_{\mathrm{advect}}$. It often takes the form
$$Q^{(\mathrm{c})}_{\mathrm{advect}} = Q^{\mathrm{mass}}\,C_{\mathrm{m}}, \tag{1.4}$$
where Q^{mass} is the mass per time per horizontal area of water entering or leaving the ocean through liquid or frozen precipitation, evaporation, liquid runoff, and solid calving. The concentration C_{m} is that in the boundary water flux. This concentration is generally zero for salinity. For temperature, the precipitation and evaporation are assumed to have the temperature of the sea surface temperature. For the land model (LM3) used in ESM2M, liquid runoff and solid calving have a heat content relative to $0°C$ that is transferred to the ocean, so that we do not need to assume a temperature for this water.
- $Q^{(\mathrm{c})}_{(\mathrm{bot})}$ is the flux of tracer passed into the liquid ocean through the solid bottom boundary. ESM2M has a non-zero geothermal heat flux that is static in time but spatially varying.
- $Q^{(\mathrm{c})}_{\mathrm{non\text{-}advect}}$ is the non-advective flux of tracer crossing the ocean surface boundary. The sign is defined so that a positive value represents a flux of tracer into the ocean; e.g., positive sign adds heat, salt, carbon, or other tracers to the ocean. For the heat budget, this term arises from shortwave, longwave, latent, and sensible heat fluxes.

1.2 Conventions for the heat budget terms

Following from the tracer budget given by equations (1.1a)-(1.1c), all heat budget terms directly diagnosed from MOM5 take the general form

$$Q_{\text{process(n)}} = \mathrm{C}_{\mathrm{p}}^{o} \left(\frac{\partial (\rho_0 \, \mathrm{d}z \, \Theta)}{\partial t} \right)_{\text{process(n)}} \qquad \text{Watt m}^{-2}, \tag{1.5}$$

where n labels the particular physical process. The heat capacity is given by

$$\mathrm{C}_{\mathrm{p}}^{o} \approx 3992.1 \text{ J kg}^{-1} \text{ K}^{-1} \tag{1.6}$$

and is assumed constant (see Section 1.3.1). The physical units for the heat budget terms are thus given by

$$Q_{\text{process(n)}} \; [\equiv] \; \text{Watt m}^{-2}. \tag{1.7}$$

The area normalization for each budget term corresponds to the horizontal area of the tracer grid cell

$$\mathrm{d}x \, \mathrm{d}y = \mathtt{area\_t}, \tag{1.8}$$

where `area_t` is the notation for the area saved as output from MOM5. Multiplication of any budget term by the tracer grid cell horizontal area thus yields the heat content change for that grid cell in units of Watts

$$\mathtt{area\_t} \, * \, Q_{\text{process(n)}} \; [\equiv] \; \text{Watt}. \tag{1.9}$$

The heat budget terms (1.5) diagnosed in MOM5 scale according to the thickness of a cell. This is expected, since the budgets computed in MOM5 are for heat per horizontal area of a cell. Nonetheless, for diagnostic purposes, it is useful to determine the budget in units of K s^{-1} in order to remove dependence on the grid cell thickness. That is, we choose to consider the budget for an intensive quantity, temperature, rather than an extensive quantity, heat. For this purpose, we divide the heat budget terms in equation (1.5) according to

$$\boxed{\delta\Theta_{\text{process(n)}} = \frac{Q_{\text{process(n)}}}{\mathrm{C}_{\mathrm{p}}^{o} \, \rho_0 \, \mathrm{d}z} \; [\equiv] \; \text{K s}^{-1}.} \tag{1.10}$$

The $\rho_0 \, \mathrm{d}z$ array saved from MOM5 diagnostics for a tracer grid cell is written

$$\mathtt{rho\_dzt} = \rho_0 \, \mathrm{d}z \qquad \text{Boussinesq ocean.} \tag{1.11}$$

1.3 Boundary heat fluxes impacting the ocean

There are three general forms of boundary heat fluxes that impact on the ocean heat content.

- Ocean heat is impacted by radiative transfer, such as shortwave heat entering the ocean or longwave radiation back to the atmosphere. Shortwave radiation is special since it generally can penetrate into the ocean interior according to the optical properties of seawater.
- Turbulent exchanges impact on the sensible and latent heat fluxes that alter ocean heat content.
- As matter crosses the ocean surface, it carries with is a non-zero heat content as measured with respect to an arbitrary reference, taken as $0°C$ for our purposes. This transfer of heat can be thought of as arising through an advective processes, whereby mass is “advected” across the ocean surface and carries with it some heat.

We discuss these heat fluxes in the remainder of this subsection.

1.3.1 Non-advective surface heat fluxes

We identify the following non-advective heat fluxes that cross the surface ocean boundary (generally considered in the SI units of W m^{-2}),

$$Q^{\text{heat}}_{\text{non-advect}} = Q_{\text{SW}} + Q_{\text{LW}} + Q_{\text{sens}} + Q_{\text{lat}} + Q_{\text{frazil}} \tag{1.12}$$

with a sign convention chosen so that positive fluxes add heat to the liquid seawater. Ocean models typically time step an equation for ocean temperature rather than heat content. So it is necessary to convert between heat and temperature fluxes when considering the impacts on sea level. As noted by McDougall (2003), to convert from heat fluxes to fluxes of potential temperature requires the use of a non-constant specific heat capacity, which varies by roughly 5% over the globe. In contrast, converting between heat fluxes and conservative temperature fluxes is done with a constant specific heat capacity

$$Q^{\text{heat}}_{\text{surface flux}} = \text{C}^{o}_{\text{p}}\, Q^{(\Theta)}_{\text{surface}}, \tag{1.13}$$

thus serving to further promote the use of conservative temperature. Nonetheless, we ignore this distinction in ESM2M, and so assume the prognostic temperature variable to be potential temperature, but take a constant heat capacity to convert between heat fluxes and temperature fluxes.

We now summarize the various heat flux contributions at the ocean surface.

- SHORTWAVE: The dominant heating occurs through the shortwave contribution $Q_{\text{SW}} > 0$. Shortwave radiation penetrates on the order of 10m to 100m into the ocean interior, with the distance depending on optical properties of seawater (see, e.g., Sweeney et al., 2005, and cited references).

- LONGWAVE: The longwave contribution Q_{LW} represents the net longwave energy that is re-radiated back to the atmosphere. Even though there are many occasions for backscattering, the net effect of longwave radiation is to cool the ocean.

- SENSIBLE: Sensible heating Q_{sens} arises from turbulent exchange with the atmosphere, and is generally parameterized by turbulent bulk formula. The sensible heat term typically cools the ocean surface.

- LATENT: Latent heating Q_{lat} cools the ocean, as it is the energy extracted from the ocean to vaporize liquid water that enters the atmosphere. Additionally, the latent heating term includes heat extracted from the ocean to melt solid runoff (i.e., calving land ice) or snow entering the liquid ocean. These latent heat terms are thus related to mass transport across the ocean surface according to

$$Q^{\text{vapor}}_{\text{lat}} = H^{\text{vapor}}\, Q^{\text{evap}}_{\text{m}} \tag{1.14}$$
$$Q^{\text{melt}}_{\text{lat}} = H^{\text{fusion}}\, (Q^{\text{calving}}_{\text{m}} + Q^{\text{snow}}_{\text{m}}), \tag{1.15}$$

  where $H^{\text{vapor}} \approx 2.5 \times 10^{6}$ J kg^{-1} is the latent heat of vaporization, $Q^{\text{evap}}_{\text{m}}$ is the evaporative mass flux in units of kg m^{-2} s^{-1}, $H^{\text{fusion}} \approx 3.34 \times 10^{5}$ J kg^{-1} is the latent heat of fusion, $Q^{\text{calving}}_{\text{m}}$ is the mass flux of calving land ice entering the ocean, and $Q^{\text{snow}}_{\text{m}}$ is the mass flux of frozen precipitation falling on the ocean surface. Note that sea ice and frozen precipitation may enter the ocean at a temperature below the freezing point, in which case additional heat needs to be extracted from the liquid ocean to raise the frozen water to the melting point.

- FRAZIL: As the temperature of seawater cools to the freezing point, sea ice is formed, initially through the production of frazil. Operationally in an ocean model, liquid water can be supercooled at any particular time step through surface fluxes and transport. An adjustment process heats the liquid water back to the freezing point, with this positive heat flux Q_{frazil} extracted from the ice model as frazil sea ice is formed.

1.3.2 Advective surface heat fluxes

The GFDL land model used in ESM2M carries the heat content (and tracer content) of its river water. Hence, both liquid runoff and calving land ice carry their own heat content into the ocean, computed with respect to $0°C$. No assumptions are required by the ocean model regarding the temperature of the river water, since the river model makes that decision.

In contrast, global atmospheric models generally do not carry the heat content of their condensed moisture, either liquid or solid. Hence, ocean models with real water flux boundary conditions, such as the MOM5 configuration used in ESM2M, must make an assumption regarding the heat content of water entering or leaving the ocean through air-sea interactions. Note that the heat content of mass transferred across the ocean boundary is, by convention, computed with respect to $0°C$. The question is what should we assume for the temperature of the mass that enters or leaves the ocean?

Evaporation is naively the simplest case, whereby we assume the evaporating water leaves the ocean with a temperature of the ocean surface grid cell. However, questions about bulk surface temperature versus skin temperature have not been considered, and will impact on the heat content transferred away from the ocean. Likewise, most climate models assume the liquid precipitation enters at the ocean surface temperature. This, again, is not necessarily correct, since rain may be either warmer or colder than the ocean surface temperature. But in the absence of information from an atmospheric model, setting evaporation and preciptation temperatures equal to the ocean surface grid cell temperature is the most common choice.

What about frozen precipitation (i.e., snow)? One choice is to assume it enters the ocean at the freezing point of fresh water, $0°C$. If that were assumed, then snow would not contribute to the ocean heat through MASS HEAT. It would, however, affect ocean heat through the latent heat of fusion needed to melt snow, plus the heat needed to raise or lower the melted mass to the ambient ocean temperature. For example, if snow falls on an ocean with surface temperature $10°C$, then the liquid ocean loses heat due to melting the snow, and loses heat in order to raise the melted snow to the ambient ocean temperature.

Rather than assume snow enters the ocean at $0°C$, MOM assumes snow enters as part of the liquid precipitation, and so it carries a temperature equal to the ocean surface temperature just as the liquid precipitation. Snow therefore affects the liquid ocean heat content through the heat of fusion needed to melt the snow, and through the heat content of snow relative to $0°C$. We see that this is in fact the convention by inspecting the MOM5 module `ocean_core/ocean_sbc.F90`, where

$$\text{MASS HEAT AIR-SEA} = \texttt{pme} * \texttt{tpme}, \tag{1.16}$$

where `tpme` is the temperature of the precipitation and evaporation, which is generally assumed to be the surface model temperature. The field `pme` includes both liquid and frozen precipitation

$$\texttt{pme} = \texttt{lprec} + \texttt{evap} + \texttt{fprec}, \tag{1.17}$$

where all fields are signed so that positive indicates water entering the ocean surface. In summary, for computing MASS HEAT AIR-SEA as part of the time tendency for the temperature equation, MOM4 and MOM5 set the temperature of the frozen precipitation to the temperature of the liquid precipitation.

There is a net heat loss to the ocean system due to the heat transfer associated with precipitation minus evaporation. The reason is that evaporation tends to occur in warm regions whereas precipitation tends to occur in cooler regions. So the mass transport of warm water away from the ocean and cooler water into the ocean represents a net loss of heat to the ocean. Delworth et al. (2006) estimated the heat loss in CM2.1 to be roughly -0.15 W m^{-2}. We need to perform this analysis for ESM2M using the online diagnostics.

1.3.3 Diagnostics for surface heat flux

The available MOM5 diagnostics for computing surface heat fluxes are as follows (all have units of W m^{-2}):

$$\text{RADIATIVE} = \texttt{swflx} + \texttt{lw\_heat} \tag{1.18a}$$

$$\text{TURBULENT} = \texttt{sens\_heat} + \texttt{calving\_melt\_heat} + \texttt{evap\_heat} + \texttt{fprec\_melt\_heat} \tag{1.18b}$$

$$\text{MASS HEAT} = \texttt{sfc\_hflux\_from\_calving} + \texttt{sfc\_hflux\_from\_runoff} + \texttt{sfc\_hflux\_pme} \tag{1.18c}$$

$$\text{FRAZIL} = \texttt{frazil\_2d} \tag{1.18d}$$

$$\text{NET SURFACE HEAT FLUX} = \text{RADIATIVE} + \text{TURBULENT} + \text{MASS HEAT} + \text{FRAZIL}. \tag{1.18e}$$

It is often the case that we are interested in the heat flux that passes through the coupler, which only includes the non-advective fluxes, in which case

$$\texttt{sfc\_hflux\_coupler} = \texttt{swflx} + \texttt{lw\_heat} + \texttt{sens\_heat} + \texttt{calving\_melt\_heat} + \texttt{evap\_heat} + \texttt{fprec\_melt\_heat}. \tag{1.19}$$

For the heat content associated with river water, which can in general be liquid runoff or solid calving, we have

$$\texttt{sfc\_hflux\_river} = \texttt{sfc\_hflux\_from\_calving} + \texttt{sfc\_hflux\_from\_runoff}. \tag{1.20}$$

Hence, we may write for the net heat flux crossing the ocean surface boundary

$$\text{NET SURFACE HEAT FLUX} = \texttt{sfc\_hflux\_coupler} + \texttt{sfc\_hflux\_river} + \texttt{sfc\_hflux\_pme}. \tag{1.21}$$

1.4 Sample ocean heat budgets

We now identify those terms contributing to the ocean heat budget in ESM2M. We do so by summarizing the physical processes impacting heat within an ocean grid cell, and identifying the corresponding diagnostics available in MOM5 available for diagnosing these terms. We first detail the heat budget in the CM2.5 and CM2.6 climate models discussed by Delworth et al. (2012), since the budget is simpler in these models than ESM2M. We then present the extra terms needed for ESM2M in Section 1.4.2. Note that all terms in the following have units of Watt m^{-2}. Converting to K s^{-1} requires the division shown by equation (1.10).

1.4.1 Heat budget for an ocean grid cell in CM2.5 and CM2.6

The following physical processes impact the heat budget within an ocean grid cell in CM2.5 and CM2.6, with these processes denoted by their diagnostic name found in the model output.

- `temp_tendency`: This is the net tendency for the temperature content (i.e., heat) in a grid cell

$$\texttt{temp\_tendency} = \partial_t (\Theta \, \rho \, dz). \tag{1.22}$$

- `temp_advection`: This the convergence of the three dimensional advection flux components

$$\texttt{temp\_advection} = -\nabla_s \cdot [\rho \, dz \, \mathbf{u} \, \Theta] - [\rho \, w^{(z)} \, \Theta]_{s=s_{k-1}} + [\rho \, w^{(z)} \, \Theta]_{s=s_k}. \tag{1.23}$$

  ESM2M, CM2.5, CM2.6 use a multi-dimensional method for computing advection fluxes, in which case it is not convenient to split the terms into horizontal and vertical contributions. Hence, we diagnose this term as a three-dimensional convergence.

- `temp_submeso`: This the convergence of the three dimensional subgrid scale flux components arising from the mixed-layer submesoscale parameterization scheme of Fox-Kemper et al. (2008) as implemented according to Fox-Kemper et al. (2011) and chapter 24 of Griffies (2012)

$$\texttt{temp\_submeso} = -\nabla_s \cdot [\rho \, dz \, \mathbf{F}] - [\rho \, F^{(z)}]_{s=s_{k-1}} + [\rho \, F^{(z)}]_{s=s_k}. \tag{1.24}$$

- `temp_vdiffuse_impl`: This term contains the impacts from vertical diffusion, handled implicitly in time and including the non-advective boundary fluxes, sans frazil

$$\texttt{temp\_vdiffuse\_impl} = \left[\rho \, F^{(z)}\right]_{s=s_{k=1}} + Q_{\text{SW}} + Q_{\text{LW}} + Q_{\text{sens}} + Q_{\text{lat}} \qquad \text{k=1} \tag{1.25a}$$

$$\texttt{temp\_vdiffuse\_impl} = -[\rho \, F^{(z)}]_{s=s_{k-1}} + [\rho \, F^{(z)}]_{s=s_k} \qquad 1 < \text{k} < \text{kbot} \tag{1.25b}$$

$$\texttt{temp\_vdiffuse\_impl} = -\left[\rho \, F^{(z)}\right]_{s=s_{kbot-1}} + Q_{\text{bottom}}^{\text{heat}} \qquad \text{k=kbot}. \tag{1.25c}$$

  In these expressions, the flux component $F^{(z)}$ is that from downgradient vertical tracer diffusion. The surface heat flux components are defined by equation (1.12). The CM2.5 and CM2.6 simulations have no geothermal heating, though ESM2M has a nonzero term for $Q_{\text{bottom}}^{\text{heat}}$.

It is useful to diagnose the impacts on heat from vertical diffusion due to a vertical diffusivity separately to the impacts from boundary heat fluxes. For this purpose, we make use of the following diagnostic identity

$$\texttt{temp\_vdiffuse\_impl} = \texttt{temp\_vdiffuse\_sbc} + \texttt{temp\_vdiffuse\_diff\_cbt}, \tag{1.26}$$

where `temp_vdiffuse_diff_cbt` arises just from a nonzero vertical diffusivity, and

$$\texttt{temp\_vdiffuse\_sbc} = Q_{\text{SW}} + Q_{\text{LW}} + Q_{\text{sens}} + Q_{\text{lat}} \tag{1.27}$$

arises from the non-advective surface boundary fluxes. Another way to capture the split found in equation (1.26), without introducing a new diagnostic term, is to make use of the identity

$$\sum_{k=1}^{\text{kbot}} \texttt{temp\_vdiffuse\_impl}[k] = \texttt{temp\_vdiffuse\_sbc}, \tag{1.28}$$

which follows from equations (1.25a)–(1.25c).

- `temp_nonlocal_kpp`: This term accounts for the non-local tendency arising from the KPP boundary layer parameterization. It acts to rearrange temperature in the vertical. Hence, there is no net heating involved, so that the vertical sum vanishes

  $$\sum_{k=1}^{\text{kbot}} \texttt{temp\_nonlocal\_kpp}[k] = 0. \tag{1.29}$$

  Further details of the KPP scheme are provided in Chapter 18 of Griffies (2012).

- `sw_heat`: This term accounts for the penetrative heating from shortwave radiation, with details given in Chapter 17 of Griffies (2012). Note in particular the discussion in Section 17.4 that details how to avoid double counting the impacts from shortwave, with the bottomline from that discussion being

  $$\text{net shortwave radiation heating at } (k=1) = \texttt{swflx} + \texttt{sw\_heat}(k=1). \tag{1.30}$$
  $$\text{net shortwave radiation heating at } (k>1) = \texttt{sw\_heat}(k>1). \tag{1.31}$$

  Since the penetrative radiation term `sw_heat` only acts to redistribute the radiation through the column, it has a zero vertical sum

  $$\sum_{k=1}^{\text{kbot}} \texttt{sw\_heat}[k] = 0. \tag{1.32}$$

- `temp_rivermix`: This term accounts for the heating associated with the introduction of river runoff over the upper four model grid cells, with details given in Chapter 28 in Griffies (2012). Note the identity

  $$\sum_{k=1}^{\text{kbot}} \texttt{temp\_rivermix}[k] = \texttt{sfc\_hflux\_runoff} + \texttt{sfc\_hflux\_calving}, \tag{1.33}$$

  where `sfc_hflux_runoff` and `sfc_hflux_calving` are the heat flux, relative to $0°C$, associated with the transfer of liquid runoff and solid calving. River water is mixed into the upper four grid cells in CM2.5, CM2.6, and ESM2M.

- `sfc_hflux_pme`: This term accounts for the heating associated with the passage of precipitation and evaporation across the ocean surface, with heat flux computed relative to $0°C$.

- `temp_eta_smooth`: This term accounts for the heating in the k=1 cell associated with smoothing the free surface to reduce the impacts from the checker-board null mode. Details are given in Chapter 31 of Griffies (2012).

- `frazil_2d`: The diagnostic `frazil_2d` measures the heat impact on the ocean due to frazil formation.

The following provides a diagnostic accounting of the ocean heat budget for a grid cell in CM2.5 and CM2.6

$$\begin{aligned}
\texttt{temp\_tendency}(k=1) &= \texttt{temp\_advection} + \texttt{temp\_submeso} \\
&+ \texttt{temp\_vdiffuse\_diff\_cbt} + \texttt{temp\_nonlocal\_KPP} + \texttt{sw\_heat} \\
&+ \texttt{temp\_rivermix} \\
&+ \texttt{temp\_vdiffuse\_sbc} + \texttt{sfc\_hflux\_pme} + \texttt{frazil\_2d} + \texttt{temp\_eta\_smooth} \quad (1.34) \\
\texttt{temp\_tendency}(1 < k \le 4) &= \texttt{temp\_advection} + \texttt{temp\_submeso} \\
&+ \texttt{temp\_vdiffuse\_diff\_cbt} + \texttt{temp\_nonlocal\_KPP} + \texttt{sw\_heat} \\
&+ \texttt{temp\_rivermix} \quad (1.35) \\
\texttt{temp\_tendency}(4 < k) &= \texttt{temp\_advection} + \texttt{temp\_submeso} \\
&+ \texttt{temp\_vdiffuse\_diff\_cbt} + \texttt{temp\_nonlocal\_KPP} + \texttt{sw\_heat}. \quad (1.36)
\end{aligned}$$

1.4.2 Heat budget for an ocean grid cell in ESM2M

The coarse resolution ocean in ESM2M has a heat budget that is modified relative to CM2.5 and CM2.6 due to the introduction of a number of new subgrid scale parameterizations.

1.4.2.1 Mesoscale eddy parameterizations

Those terms arising from the use of mesoscale eddy parameterization are as follows

- `neutral_gm_temp`: This term arises from the convergence of the three dimensional subgrid scale flux components from the Gent and McWilliams (1990) scheme, with the implementation in CM_O1.0_C180 following the methods from Ferrari et al. (2010).
- `neutral_diffusion_temp`: This term arises from the convergence of the three dimensional subgrid scale flux components in the time-explicit portion of the neutral diffusion scheme.
- `temp_vdiffuse_k33`: This term arises from the vertical K33 portion of the neutral diffusion operator that is handled implicitly in time. Note that this term is contained already in the diagnostic `temp_vdiffuse_impl`. The following identity holds

  $$\texttt{temp\_vdiffuse\_impl} = \texttt{temp\_vdiffuse\_sbc} + \texttt{temp\_vdiffuse\_diff\_cbt} + \texttt{temp\_vdiffuse\_k33}. \quad (1.37)$$

  It is very useful to split the `temp_vdiffuse_diff_cbt` term, arising from dianeutral mixing processes, from `temp_vdiffuse_k33`, arising from rotated neutral diffusion.

We also need to diagnose the contributions to the vertically integrated meridional heat transport from these two processes as available in the diagnostics

- `temp_xflux_ndiffuse_int_z`
- `temp_yflux_ndiffuse_int_z`
- `temp_xflux_gm_int_z`
- `temp_yflux_gm_int_z`.

1.4.2.2 Cross land mixing

Those terms associated with mixing properties across marginal seas whose straights are not resolved by the grid include

- `temp_xlandmix` and `temp_xlandinsert`: These terms arise from the exchange of volume and tracer between the open ocean and marginal seas, with details given in Chapters 29 and 30 of Griffies (2012).

1.4.2.3 Overflow parameterizations

Schemes used to help parameterize downslope overflow processes include

- `mixdownslope_temp`: This term arises from the convergence of the fluxes associated with the mixdownslope parameterization scheme detailed in Section 27.4 of Griffies (2012). Note that there is a diagnostic error in ESM2M associated with `mixdownslope_temp`. Namely, there is a diagnosed contribution from `mixdownslope_temp` in the Black Sea, whereas the prognostic model masked this contribution to zero. Hence, there is no change to the ocean heat content from `mixdownslope_temp` in the Black Sea. To resolve the diagnostic bug, one should multiply `mixdownslope_temp` by zero just within the Black Sea.

- `temp_sigma_diff`: This term arises from the sigma-diffusion scheme from Beckmann and Döscher (1997) as detailed in Section 27.2.1 of Griffies (2012).

1.4.2.4 Liquid river runoff and solid calving land ice

Water from the land enters the ocean either as a liquid runoff or a solid calving land ice.

- `temp_runoffmix`: This term arises from the contributions to the ocean heating from liquid runoff contained in the land-model.

- `temp_calvingmix`: This term arises from the contributions to the ocean heating from solid runoff contained in the land-model. In ESM2M, this term is split from `temp_runoffmix` and so needs to be diagnosed separately, whereas it is combined with `temp_runoffmix` in CM2.5 and CM2.6.

1.4.2.5 Geothermal heating

Geothermal heating is applied as a lower boundary condition to the vertical diffusion equation. It can be diagnosed through the following identity

- `geo_heat`: This term arises from the static geothermal heating applied to the ocean bottom. The geothermal heat flux is applied to the tracer equation as a lower boundary condition to the vertical diffusion equation. Therefore, the identity (1.28) for CM2.5 and CM2.6 takes the following form in ESM2M

$$\sum_{k=1}^{\text{kbot}} \texttt{temp\_vdiffuse\_impl}[k] = \texttt{temp\_vdiffuse\_sbc} + \texttt{geo\_heat}. \tag{1.38}$$

1.4.2.6 Summary of the ESM2M heat budget

So in summary, the terms required for the ESM2M heat budget are the following:

$$\begin{aligned}
\texttt{temp\_tendency}[\text{ESM2M}](k=1) &= \texttt{temp\_advection} + \texttt{temp\_submeso} \\
&+ \texttt{neutral\_diffusion\_temp} + \texttt{neutral\_gm\_temp} + \texttt{temp\_vdiffuse\_k33} \\
&+ \texttt{temp\_vdiffuse\_diff\_cbt} + \texttt{temp\_nonlocal\_KPP} + \texttt{sw\_heat} \\
&+ \texttt{temp\_runoffmix} + \texttt{temp\_calvingmix} \\
&+ \texttt{temp\_xlandmix} + \texttt{temp\_xlandinsert} \\
&+ \texttt{mixdownslope\_temp} + \texttt{temp\_sigma\_diff} \\
&+ \texttt{temp\_vdiffuse\_sbc} + \texttt{sfc\_hflux\_pme} + \texttt{frazil\_2d} + \texttt{temp\_eta\_smooth}
\end{aligned} \tag{1.39a}$$

$$\begin{aligned}
\texttt{temp\_tendency}[\text{ESM2M}](1<k\le 4) &= \texttt{temp\_advection} + \texttt{temp\_submeso} \\
&+ \texttt{neutral\_diffusion\_temp} + \texttt{neutral\_gm\_temp} + \texttt{temp\_vdiffuse\_k33} \\
&+ \texttt{temp\_vdiffuse\_diff\_cbt} + \texttt{temp\_nonlocal\_KPP} + \texttt{sw\_heat} \\
&+ \texttt{temp\_runoffmix} + \texttt{temp\_calvingmix} \\
&+ \texttt{temp\_xlandmix} + \texttt{temp\_xlandinsert} \\
&+ \texttt{mixdownslope\_temp} + \texttt{temp\_sigma\_diff} \\
&+ \texttt{geo\_heat}[\texttt{k} = \texttt{kbot}]
\end{aligned} \tag{1.39b}$$

$$\begin{aligned}
\texttt{temp\_tendency}[\text{ESM2M}](4<k) &= \texttt{temp\_advection} + \texttt{temp\_submeso} \\
&+ \texttt{neutral\_diffusion\_temp} + \texttt{neutral\_gm\_temp} + \texttt{temp\_vdiffuse\_k33} \\
&+ \texttt{temp\_vdiffuse\_diff\_cbt} + \texttt{temp\_nonlocal\_KPP} + \texttt{sw\_heat} \\
&+ \texttt{temp\_xlandmix} + \texttt{temp\_xlandinsert} \\
&+ \texttt{mixdownslope\_temp} + \texttt{temp\_sigma\_diff} \\
&+ \texttt{geo\_heat}[\texttt{k} = \texttt{kbot}].
\end{aligned} \tag{1.39c}$$

1.5 Summary of the ESM2M heat budget diagnostics

We summarize in Table 1.5 the terms required for the ESM2M heat budget and Table 1.5 shows ancilliarly terms available for further analysis. The net archive requirement for each experiment is roughly 53Gb, making the total for the three experiments around 160Gb.

FIELDNAME	UNITS	LEVELS	SIZE PER 100YR	YEARS	TOTAL SIZE
`calving_melt_heat`	W m^{-2}	1	29Mb	1-100 + 101-200	58Mb
`evap_heat`	W m^{-2}	1	29Mb	1-100 + 101-200	58Mb
`fprec_melt_heat`	W m^{-2}	1	29Mb	1-100 + 101-200	58Mb
`frazil_2d`	W m^{-2}	1	29Mb	1-100 + 101-200	58Mb
`lw_heat`	W m^{-2}	1	29Mb	1-100 + 101-200	58Mb
`mixdownslope_temp`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`neutral_diffusion_temp`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`neutral_gm_temp`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`sens_heat`	W m^{-2}	1	29Mb	1-100 + 101-200	58Mb
`sfc_hflux_from_calving`	W m^{-2}	1	29Mb	1-100 + 101-200	58Mb
`sfc_hflux_from_runoff`	W m^{-2}	1	29Mb	1-100 + 101-200	58Mb
`sfc_hflux_pme`	W m^{-2}	1	29Mb	1-100 + 101-200	58Mb
`swflx`	W m^{-2}	1	29Mb	1-100 + 101-200	58Mb
`sw_heat`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_advection`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_calvingmix`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_eta_smooth`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_nonlocal_KPP`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_runoffmix`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_sigma_diff`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_submeso`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_tendency`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_vdiffuse_diff_cbt`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_vdiffuse_impl`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_vdiffuse_k33`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_xlandinsert`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_xland`	W m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
Total size per experiment					49Gb

Table 1.1: Summary of the annual mean diagnostics required for use in diagnosing the ESM2M ocean heat budget. The filenames for each of the fields is determined by including either ocean.0001 − 0100. or ocean.0101 − 0200. as a prefix, depending on which century of the time series is being considered, and a suffix .nc. For example, ocean.0101 − 0200.`calving_melt_heat`.nc is the filename for `calving_melt_heat` over years 101-200. All files are provided for the three simulations (1) control, (2) $2xCO_2$, and (3) instantaneous quadrupling of CO_2. Converting the heat budget terms to units of K s^{-1} requires the division shown by equation (1.10).

FIELDNAME	UNITS	LEVELS	SIZE PER 100YR	YEARS	TOTAL SIZE
`rho_dzt`	kg m^{-2}	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp`	°C	50	1.4Gb	1-100 + 101-200	2.8Gb
`temp_xflux_gm_int_z`	W	1	29Mb	1-100 + 101-200	58Mb
`temp_xflux_ndiffuse_int_z`	W	1	29Mb	1-100 + 101-200	58Mb
`temp_xflux_sigma`	W	1	29Mb	1-100 + 101-200	58Mb
`temp_xflux_submeso_int_z`	W	1	29Mb	1-100 + 101-200	58Mb
`temp_yflux_gm_int_z`	W	1	29Mb	1-100 + 101-200	58Mb
`temp_yflux_ndiffuse_int_z`	W	1	29Mb	1-100 + 101-200	58Mb
`temp_yflux_sigma`	W	1	29Mb	1-100 + 101-200	58Mb
`temp_yflux_submeso_int_z`	W	1	29Mb	1-100 + 101-200	58Mb
Total size per experiment					6Gb

Table 1.2: Summary of the annual mean diagnostics available in support of the ocean heat budget analysis in ESM2M. The `xflux` and `yflux` diagnostics are useful to map the vertically integrated heat transport. The filenames for each of the fields is determined by including either $\mathrm{ocean.0001-0100.}$ or $\mathrm{ocean.0101-0200.}$ as a prefix, depending on which century of the time series is being considered, and a suffix $\mathrm{.nc}$. For example, $\mathrm{ocean.0101-0200.}$`rho_dzt`$\mathrm{.nc}$ is the filename for `rho_dzt` over years 101-200. All files are provided for the three simulations (1) control, (2) $2xCO_2$, and (3) instantaneous quadrupling of CO_2.

Bibliography

Adcroft, A., Campin, J.-M., 2004. Rescaled height coordinates for accurate representation of free-surface flows in ocean circulation models. Ocean Modelling 7, 269–284.

Beckmann, A., Döscher, R., 1997. A method for improved representation of dense water spreading over topography in geopotential-coordinate models. Journal of Physical Oceanography 27, 581–591.

Delworth, T. L., Broccoli, A. J., Rosati, A., Stouffer, R. J., Balaji, V., Beesley, J. A., Cooke, W. F., Dixon, K. W., Dunne, J., Dunne, K. A., Durachta, J. W., Findell, K. L., Ginoux, P., Gnanadesikan, A., Gordon, C., Griffies, S. M., Gudgel, R., Harrison, M. J., Held, I. M., Hemler, R. S., Horowitz, L. W., Klein, S. A., Knutson, T. R., Kushner, P. J., Langenhorst, A. L., Lee, H.-C., Lin, S., Lu, L., Malyshev, S. L., Milly, P., Ramaswamy, V., Russell, J., Schwarzkopf, M. D., Shevliakova, E., Sirutis, J., Spelman, M., Stern, W. F., Winton, M., Wittenberg, A. T., Wyman, B., Zeng, F., Zhang, R., 2006. GFDL's CM2 global coupled climate models - Part 1: Formulation and simulation characteristics. Journal of Climate 19, 643–674.

Delworth, T. L., Rosati, A., Anderson, W., Adcroft, A. J., Balaji, V., Benson, R., Dixon, K., Griffies, S. M., Lee, H.-C., Pacanowski, R. C., Vecchi, G. A., Wittenberg, A. T., Zeng, F., Zhang, R., 2012. Simulated climate and climate change in the GFDL CM2.5 high-resolution coupled climate model. Journal of Climate 25, 2755–2781.

Dunne, J. P., John, J. G., Hallberg, R. W., Griffies, S. M., Shevliakova, E. N., Stouffer, R. J., Krasting, J. P., Sentman, L. A., Milly, P. C. D., Malyshev, S. L., Adcroft, A. J., Cooke, W., Dunne, K. A., Harrison, M. J., Levy, H., Samuels, B. L., Spelman, M., Winton, M., Wittenberg, A. T., Phillips, P. J., Zadeh, N., 2012. GFDLs ESM2 global coupled climate-carbon Earth System Models Part I: Physical formulation and baseline simulation characteristics. Journal of Climate 25, 6646–6665.

Ferrari, R., Griffies, S. M., Nurser, A. J. G., Vallis, G. K., 2010. A boundary-value problem for the parameterized mesoscale eddy transport. Ocean Modelling 32, 143–156.

Fox-Kemper, B., Danabasoglu, G., Ferrari, R., Griffies, S. M., Hallberg, R. W., Holland, M., Peacock, S., Samuels, B., 2011. Parameterization of mixed layer eddies. III: Global implementation and impact on ocean climate simulations. Ocean Modelling 39, 61–78.

Fox-Kemper, B., Ferrari, R., Hallberg, R., 2008. Parameterization of mixed layer eddies. I: Theory and diagnosis. Journal of Physical Oceanography 38, 1145–1165.

Gent, P. R., McWilliams, J. C., 1990. Isopycnal mixing in ocean circulation models. Journal of Physical Oceanography 20, 150–155.

Griffies, S. M., 2012. Elements of the Modular Ocean Model (MOM): 2013 release (GFDL Ocean Group Technical Report No. 7). NOAA/Geophysical Fluid Dynamics Laboratory, Princeton, USA, 614 + xiii pages.

McDougall, T. J., 2003. Potential enthalpy: a conservative oceanic variable for evaluating heat content and heat fluxes. Journal of Physical Oceanography 33, 945–963.

Stacey, M. W., Pond, S., Nowak, Z. P., 1995. A numerical model of the circulation in Knight Inlet, British Columbia, Canada. Journal of Physical Oceanography 25, 1037–1062.

Sweeney, C., Gnanadesikan, A., Griffies, S. M., Harrison, M., Rosati, A., Samuels, B., 2005. Impacts of shortwave penetration depth on large-scale ocean circulation and heat transport. Journal of Physical Oceanography 35, 1103–1119.