Detailing the heat tracers in FAFMIP

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Abstract

These notes detail the three heat tracers proposed for FAFMIP. The presentation may be useful to those implementing and interepreting the heat perturbation experiments. Certain of these details should be placed in the FAFMIP manuscript, since they are crucial aspects of the experimental design and easily missed with the present documentation.

Contents

1 Notation from Section 9 of Griffies et al. (2016)

In writing the heat equations below, we make use of a finite volume thickness weighted tracer notation. This notation is described in Section 9 of Griffies et al. (2016), which presents the FAFMIP tracer budget diagnostics. In summary, we have

- $\rho\,\mathrm{d}z$ is the mass per horizontal area of a grid cell, with ρ the *in situ* density and $\mathrm{d}z$ the cell thickness;
- $\mathrm{d}A$ is the static horizontal grid cell area;
- c_p^o is the constant heat capacity of seawater (McDougall, 2003);
- $c_p^o\,\theta\,\rho\,\mathrm{d}z\,\mathrm{d}A$ is the heat content of the grid cell (joule);
- $c_p^o\,\theta\,\rho\,\mathrm{d}z$ is the heat content per horizontal grid cell area ((joule/m^2).
- When making the Boussinesq approximation, we set ρ to the constant reference density ρ_o.

2 FAFMIP heat tracers

We here document the three heat related tracers considered in the FAF-heat experiment.

2.1 Potential or Conservative temperature

The potential or Conservative temperature field, θ, affects the seawater density. It satisfies the following equation for a surface ocean grid cell

$$\frac{\partial\,(\theta\,\rho\,\mathrm{d}z)}{\partial t} = \mathrm{ADV}(\boldsymbol{v},\theta) + \mathrm{SGS}(\kappa,\theta) + Q^{\theta}_{\text{advect}} + Q^{\theta}_{\text{frazil}} + Q^{TR}_{\text{non-advect}} + Q_{\text{FAF}}. \tag{1}$$

We now detail the terms appearing in equation (1).

- ADVECTION of θ is represented by $\mathrm{ADV}(\boldsymbol{v},\theta)$, where $\boldsymbol{v}$ is the three-dimensional current vector.
- SUBGRID SCALE PROCESSES are represented by $\mathrm{SGS}(\kappa,\theta)$, with κ symbolizing any number of diffusivites or non-local processes associated with the parameterized subgrid scale.

- ADVECTIVE HEAT FLUX $Q^{\theta}_{\text{advect}}$ arises from the transfer of water across the ocean boundary through precipitation, evaporation, and runoff. Note that $Q^{\theta}_{\text{advect}} = 0$ in an ocean model that does not transfer mass across its boundary, such as a rigid lid or linear free surface ocean model. However, for real water flux models, it is important to note how $Q^{\theta}_{\text{advect}}$ is computed.
  - $Q^{\theta}_{\text{advect}}$ is often determined by assuming temperature of the water equals to the sea surface temperature, $\theta_{k=1}$. This assumption is reasonable for evaporation. However, it is not accurate for precipitation, whose temperature is generally different from the sea surface. Nonetheless, the assumption is perhaps the best available since atmospheric models typically ignore the heat content of its condensed water. By assuming precipitation and evaporation have the sea surface temperature $\theta_{k=1}$, the nonzero heat flux $Q^{\theta}_{\text{advect}}$ does not locally alter $\theta_{k=1}$. However, the heat flux does alter the ocean heat content, and it will alter ocean temperature after entering the ocean interior.
  - Land models often carry the heat content of its river water, in which case the ocean is a recipient of the heat, and no assumption is needed for temperature of the runoff. However, if the land model does not provide the runoff heat content, then the heat content is also generally determined by setting its temperature to the sea surface.
- FRAZIL HEAT FLUX $Q^{\theta}_{\text{frazil}}$ is used to keep the potential temperature no lower than the freezing point of seawater. In a non-FAFMIP simulation, this heat is extracted from the sea ice model to produce sea ice. But for FAFMIP, it is the frazil term Q^{TR}_{frazil} that is exchanged with sea ice, whereas the frazil heat flux $Q^{\theta}_{\text{frazil}}$ is ignored by the sea ice model.
- NON-ADVECTIVE HEAT FLUX $Q^{TR}_{\text{non-advect}}$ includes latent, sensible, longwave, and shortwave contributions. Importantly, this flux in FAFMIP is determined by the redistributed heat tracer, T^R, discussed in Section 2.2.
- PERTURBATION HEAT FLUX Q_{FAF} is the prescribed FAFMIP perturbation flux based on CMIP5 climate change simulations.

2.2 Redistributed heat tracer

The redistribued heat tracer, T^R, does not affect ocean density, yet it does affect the surface fluxes. It is initialized to θ at the start of the simulation and it satisfies the following equation

$$\frac{\partial\,(T^R\,\rho\,\mathrm{d}z)}{\partial t} = \mathrm{ADV}(\boldsymbol{v}, T^R) + \mathrm{SGS}(\kappa, T^R) + Q^{TR}_{\text{advect}} + Q^{TR}_{\text{frazil}} + Q^{TR}_{\text{non-advect}}. \tag{2}$$

As defined, T^R does *not* feel the perturbation heat flux, Q^{FAF}. However, T^R is used to compute the non-advective heat flux, $Q^{TR}_{\text{non-advect}}$, which also impacts the potential temperature θ in equation (1). Additionally, the frazil heat, Q^{TR}_{frazil}, is extracted from the sea-ice model to produce ice. Finally, the advective heat flux, Q^{TR}_{advect}, uses T^R for its precipitation and evaporation temperature.

2.3 Added heat tracer

The added heat tracer, T^A, does not affect density nor does it impact the surface heat fluxes. It is initialized to 0°C at the start of the simulation, and represents a perturbation temperature arising from the added heat in Q^{FAF}. Consequently, it is not bound to be above the freezing point of seawater, and so does not have a frazil heating term. For the surface ocean, T^A satisfies the following equation

$$\frac{\partial\,(T^A\,\rho\,\mathrm{d}z)}{\partial t} = \mathrm{ADV}(\boldsymbol{v}, T^A) + \mathrm{SGS}(\kappa, T^A) + Q^{\text{FAF}}. \tag{3}$$

T^A thus feels the perturbation heat flux Q^{FAF}, but not the coupled heat flux $Q^{TR}_{\text{non-advect}}$. Additionally, T^A is not altered by mass transport across the ocean surface, since we assume this transport has zero added heat content, $Q^{TA}_{\text{advect}} = 0$.

3 Consistency checks

In summary, the three heat budgets for the surface ocean are given by

$$\frac{\partial\,(\theta\,\rho\,\mathrm{d}z)}{\partial t} = \mathrm{ADV}(\boldsymbol{v}, \theta) + \mathrm{SGS}(\kappa, \theta) + Q^{\theta}_{\text{advect}} + Q^{\theta}_{\text{frazil}} + Q^{TR}_{\text{non-advect}} + Q_{\text{FAF}}. \tag{4a}$$

$$\frac{\partial\,(T^R\,\rho\,\mathrm{d}z)}{\partial t} = \mathrm{ADV}(\boldsymbol{v}, T^R) + \mathrm{SGS}(\kappa, T^R) + Q^{TR}_{\text{advect}} + Q^{TR}_{\text{frazil}} + Q^{TR}_{\text{non-advect}}. \tag{4b}$$

$$\frac{\partial\,(T^A\,\rho\,\mathrm{d}z)}{\partial t} = \mathrm{ADV}(\boldsymbol{v}, T^A) + \mathrm{SGS}(\kappa, T^A) + Q^{\text{FAF}}. \tag{4c}$$

3.1 Vanishing perturbation heat flux

In the trivial case of a vanishing perturbation heat flux, $Q^{\text{FAF}} = 0$, the redistributed heat tracer and the potential temperature satisfy the same equation. Since they are initialized to be the same, they will remain the same throughout the simulation, $\theta = T^R$. This identity offers a useful check that code for the redistributed heat tracer has been properly implemented. The test can be done using the FAFpassiveheat control experiment by carrying both θ and T^R.

3.2 Sum of redistributed plus added heat

Summing the redistributed and added heat budgets leads to

$$\frac{\partial\,[(T^R + T^A)\,\rho\,\mathrm{d}z]}{\partial t} = \mathrm{ADV}(\boldsymbol{v}, T^R) + \mathrm{ADV}(\boldsymbol{v}, T^A) + \mathrm{SGS}(\kappa, T^R) + \mathrm{SGS}(\kappa, T^A) + Q^{TR}_{\text{advect}} + Q^{TR}_{\text{frazil}} + Q^{TR}_{\text{non-advect}} + Q^{\text{FAF}}. \tag{5}$$

If all terms on the right hand side act linearly, then

$$\frac{\partial\,[(T^R + T^A)\,\rho\,\mathrm{d}z]}{\partial t} = \frac{\partial\,(\theta\,\rho\,\mathrm{d}z)}{\partial t} \qquad \text{if linear budgets.} \tag{6}$$

However, the following nonlinearities prevent this equality from holding.

- FRAZIL: The redistributed tracer and the potential temperature will differ, in which case their respective frazil heats will differ. Again, we must determine a separate frazil heat for the two tracers in order to ensure that both θ and T^R have values no lower than the freezing point of seawater.
- NONLINEAR ADVECTIVE FLUXES: Most ocean models make use of flux corrections or flux limiters on their advection schemes. These methods introduce nonlinearities to the advection operator that also preclude the linear identity (6).

3.3 Penetrative shortwave heating

Both θ and T^R feel the impacts from penetrative shortwave heating, since they are both heat tracers that have a shortwave component in the the surface flux $Q^{TR}_{\text{non-advect}}$. In contrast, T^A does not feel any shortwave penetrative heating, since its surface flux, Q^{FAF}, is not split into shortwave and other constituents.

3.4 Penetrative shortwave heating and the KPP nonlocal transport

The KPP nonlocal transport (Large et al., 1994) incorportes the shortwave penetration when acting on potential or Conservative temperature. In the FAFMIP experiments, both θ and T^R feel shortwave heating, so that θ and T^R should be treated similarly for the nonlocal KPP transport. Doing so requires code modifications to MOM5, and perhaps to other codes. This issue is likely of minor consequence, since the KPP nonlocal transport is enabled only under negative buoyancy forcing (e.g., cooling), which occurs most commonly when shortwave heating is not so important.

References

Griffies, S. M., Danabasoglu, G., Durack, P., Adcroft, A., Balaji, V., Böning, C., Chassignet, E., Curchitser, E., Deshayes, J., Drange, H., Fox-Kemper, B., Gleckler, P., Gregory, J., Hallberg, R., Hewitt, H., Holland, D., Komuro, Y., Krasting, J., Large, W., Marsland, S., Masina, S., McDougall, T., Orr, J., Pirani, A., Qiao, F., Stouffer, R., Taylor, K., Tsujino, H., Uotila, P., Valdivieso, M., Winton, M., and Yeager, S.: Experimental and diagnostic protocol for the physical component of the CMIP6 Ocean Model Intercomparison Project (OMIP), Geoscientific Model Development, submitted, 2016.

Large, W., McWilliams, J., and Doney, S.: Oceanic vertical mixing: a review and a model with a nonlocal boundary layer parameterization, Reviews of Geophysics, 32, 363–403, 1994.

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