Implementation of an ultraviolet radiation damage function for phytoplankton in CESM2-MARBL

Joshua Coupe[1] and Nikki Lovenduski[1]
Collaborators: Mike Levy[2], Kristen Krumhardt[2], Keith Lindsay[2], Chuck Bardeen[3]

[1] University of Colorado Boulder
[2] CGD and [3]ACOM (NCAR)

Outline (hidden slide)

1. Introduction - why this is important
   a. research on impacts of UV radiation on phytoplankton
2. Ultraviolet radiation damage function - from Cullen et al. (1992)
   a. uses the diatom damage function from Cullen
   b. how it’s configured in TUV
   c. how it’s passed to POP->MARBL
   d. how this damage function is propagated through the column
3. Results
   a. Control run - with and without UV inhibition
   b. Halogen injection simulation - compared to control run with UV inhibition
   c. Attempt at including TUV-PAR: effect on NPP of using a different PAR
4. Conclusions and uses

Potential scenarios with enhanced surface UV radiation

- CFC induced destruction of stratospheric ozone (the Ozone Hole)
  - UV-phytoplankton laboratory studies based on this scenario (Cullen et al., 1992)
- Injection of smoke, dust, or sulfate aerosols into the stratosphere via:
  - nuclear war. (Bardeen et al., 2021)
  - wildfire producing pyrocumulonimbus clouds. (Solomon et al., 2022)
  - volcanic eruption. (Østerstrøm and Klobas et al., 2023)
  - asteroid impact. (Pierazzo et al., 2010)
- Halogen injection into the stratosphere via:
  - asteroid impact into seawater. (Pierazzo et al., 2010)

Sensitivity of phytoplankton to UV radiation

- Cullen et al. (1992) determined a biological weighting function for the inhibition of photosynthesis by UV radiation for the diatom *phaeodactylum sp*.
    - determined exponentially increasing sensitivity to UV-B radiation (280-320 nm)
- Response to UV-B is complicated by:
    - photorepair and accumulation of UV-B mitigating flavonoids at low UV-B levels.
    - sensitivity change under other climate stresses.

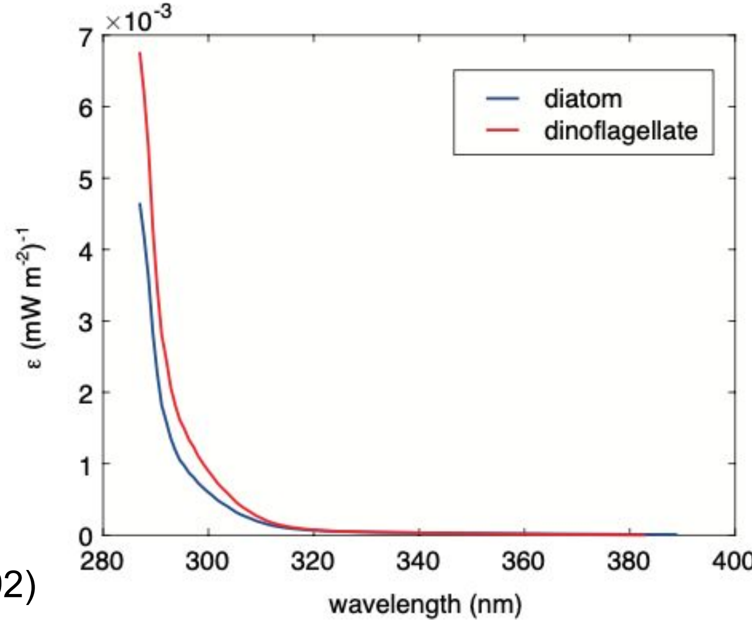


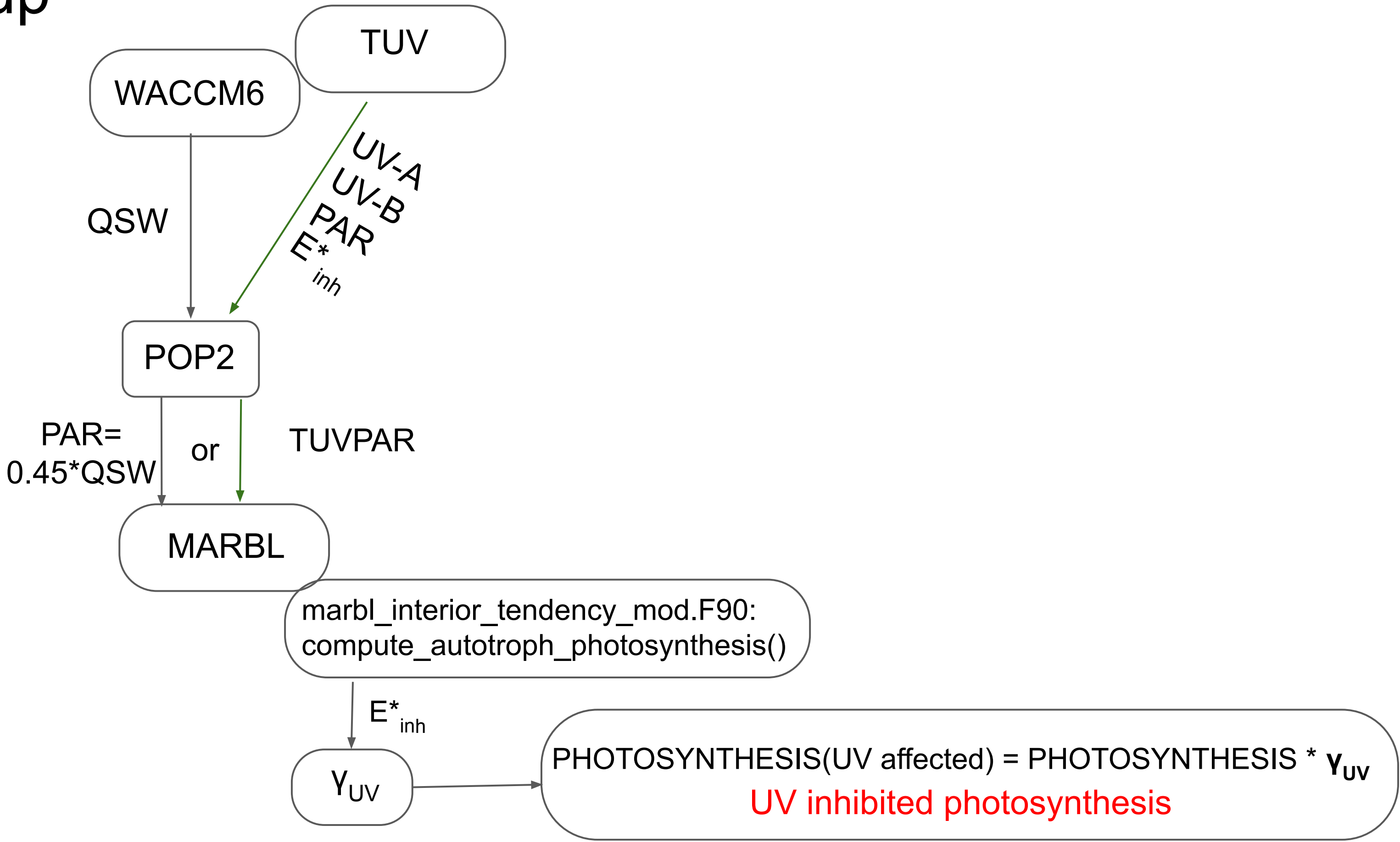
Figure 2 from Cullen et al. (1992)

Model setup

- CESM2.1.4-rel41 with WACCM6(+TUV)-CLM5-CICE-POP2-MARBL-4p2z.
  - TUV is the Tropospheric Ultraviolet and Visible Radiation Model.
  - 4p2z = 4 phytoplankton and 2 zooplankton; have tested with 3p1z and 4p1z.
- TUV is used to calculate UV radiation at the surface.
  - Cullen et al. (1992) is used to calculate UV damage function for diatoms (already built into TUV).
  - 'UV inhibition' (E^*_{inh}) is passed to MARBL
- UV limitation term [$\gamma_{UV,}$ 0-1] is constructed as a function of E*inh(z).

$$\gamma_{UV} = \frac{1}{1 + E^*_{inh}(z)}.$$

Model setup


TUV
WACCM6
QSW
UV-A
UV-B
PAR
E*inh
POP2
PAR=
0.45*QSW
or
TUVPAR
MARBL
marbl_interior_tendency_mod.F90:
compute_autotroph_photosynthesis()
E*inh
γUV
PHOTOSYNTHESIS(UV affected) = PHOTOSYNTHESIS * γUV
UV inhibited photosynthesis

Model setup

- UV limitation term [$\gamma_{UV,}$ 0-1] is constructed as a function of E*inh(z).

$$\gamma_{UV} = \frac{1}{1 + E^*_{inh}(z)}.$$

PHOTOSYNTHESIS = PHOTOSYNTHESIS*nutrient_limitation*temperature_limitation*light_limitation

PHOTOSYNTHESIS(UV affected) = PHOTOSYNTHESIS * $\boldsymbol{\gamma_{UV}}$

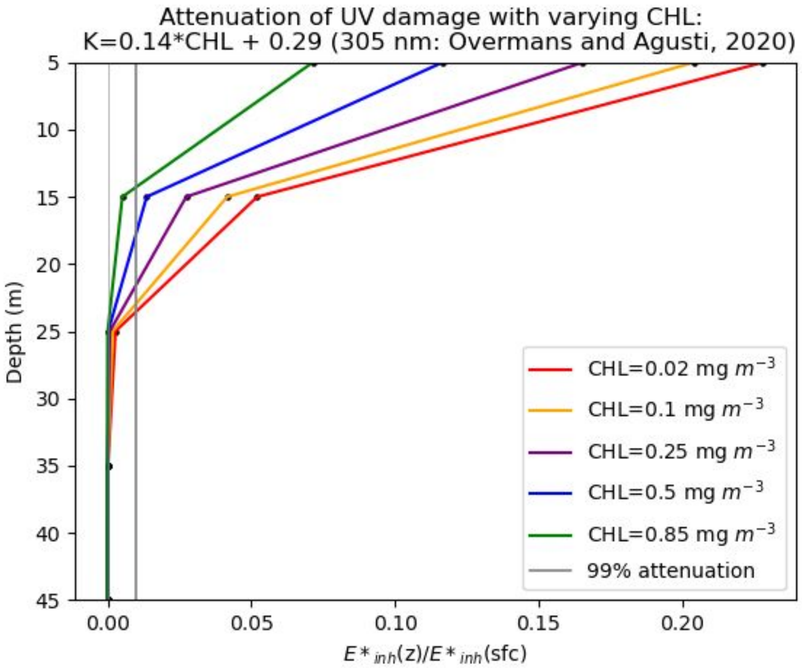
New limitation term

Model setup - water column attenuation

- E^*_{inh} is attenuated following an empirical relationship developed by Overmans and Agustí (2020):

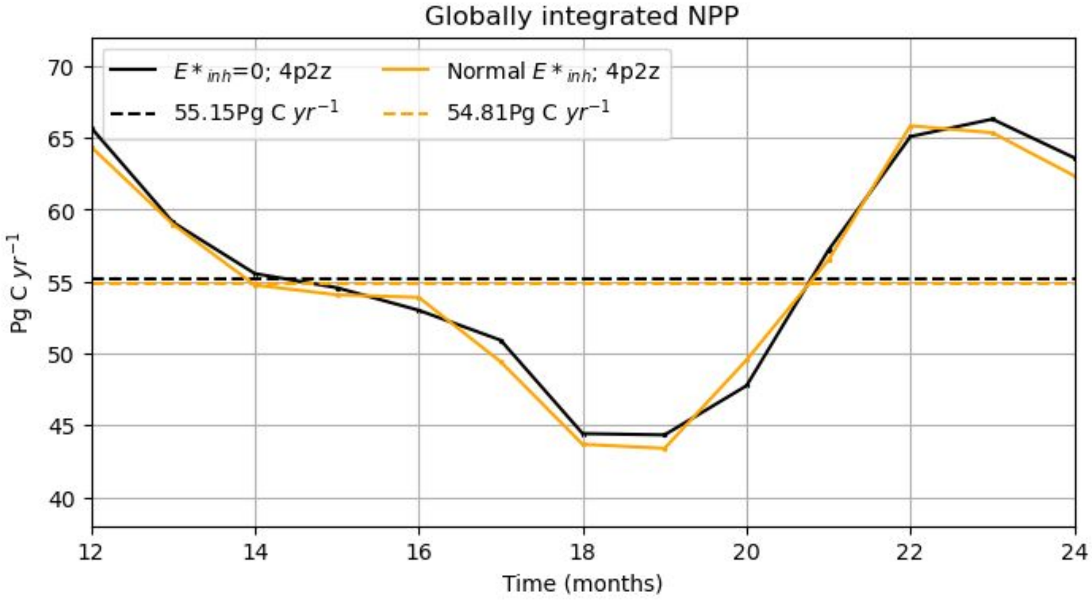
  k = 0.14*CHL + 0.29
  $E^*_{inh}(z+1) = E^*_{inh}(z) * \exp(-k*dz)$

- $E^*_{inh}(z)$ reaches 99% attenuation for most levels of chlorophyll between 15m and 25m.
  - Phytoplankton below 25m will not be impacted by enhanced UV radiation.



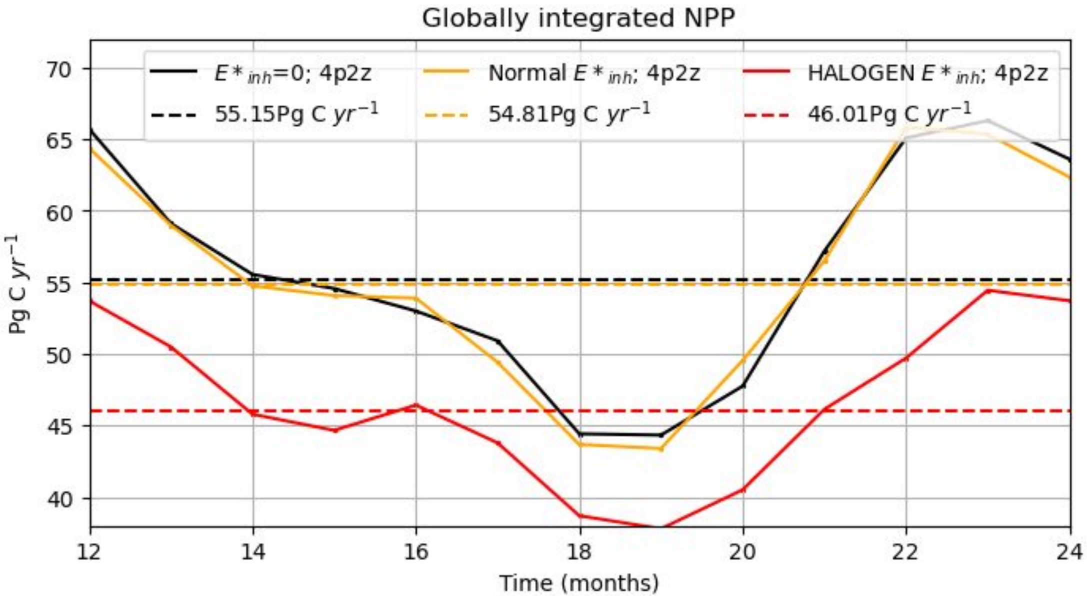
Results [preliminary]

- E^*_{inh}=0 case (γ_{UV}=1 equivalent) compared to a case with pre-industrial levels of stratospheric ozone ("Normal E*inh") shows extremely **minimal** effects:
    - 0.34 Pg C yr^{-1} reduction in NPP in year 2 of an initial spin-up period.
    - Low sensitivity to pre-industrial UV radiation levels.



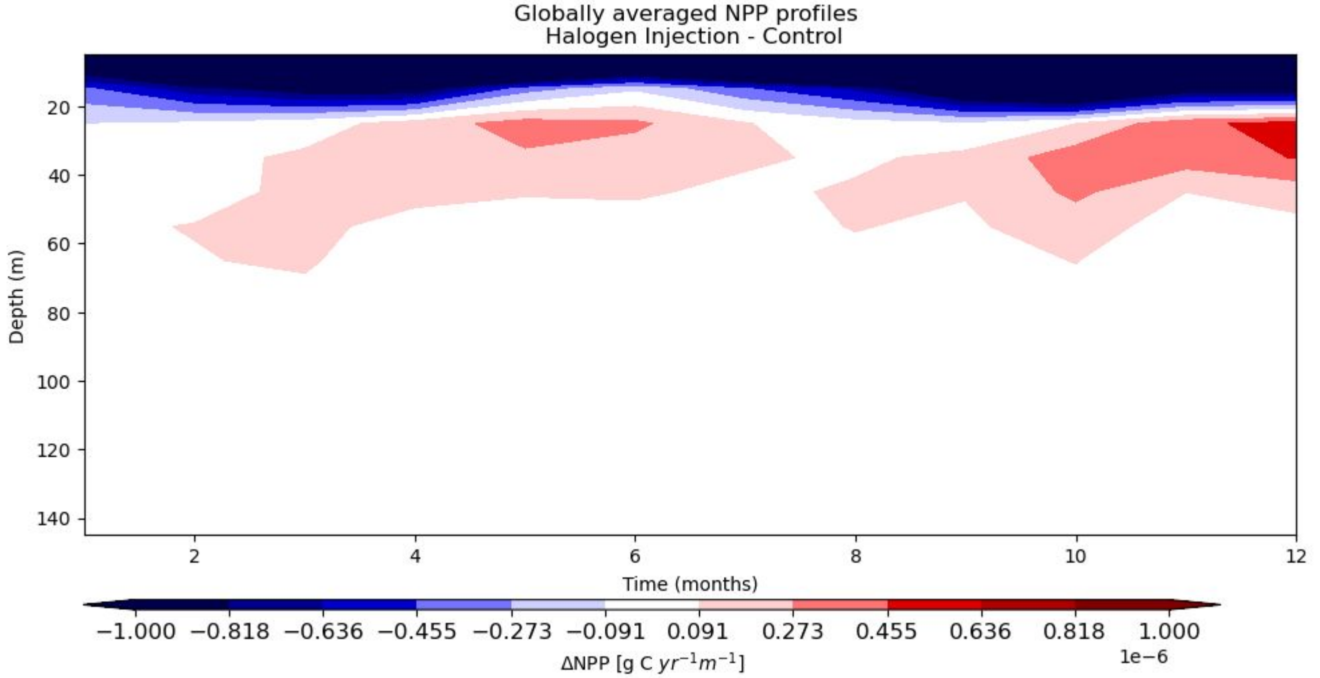
Results [preliminary]

- E^*_{inh}=0 case (γ_{UV}=1 equivalent) compared to a case with pre-industrial levels of stratospheric ozone (“Normal E*inh”) shows extremely **minimal** effects:
  - 0.34 Pg C yr^{-1} reduction in NPP in year 2 of an initial spin-up period.
- Halogen injection case causes 8.8 Pg C yr^{-1} (16%) reduction in NPP over 1-year.
  - 15-20% diminishment of ozone from 1000 Tg of Br and Cl.
  - Adapted from asteroid impact simulation that causes global ozone hole.



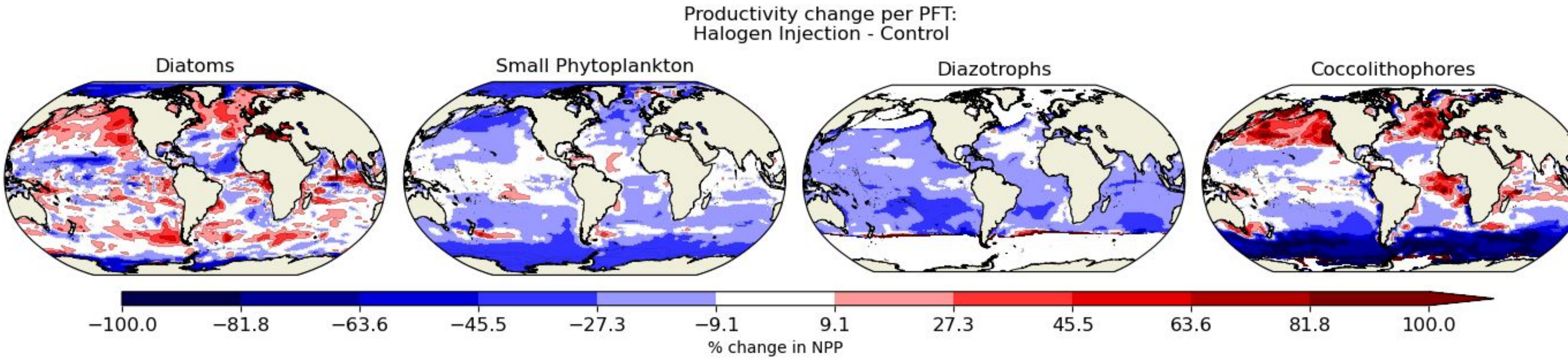
Results [preliminary] - depth dependence

- Limited depth penetration of UV radiation causes deeper phytoplankton to benefit at the expense of UV-affected surface level phytoplankton.

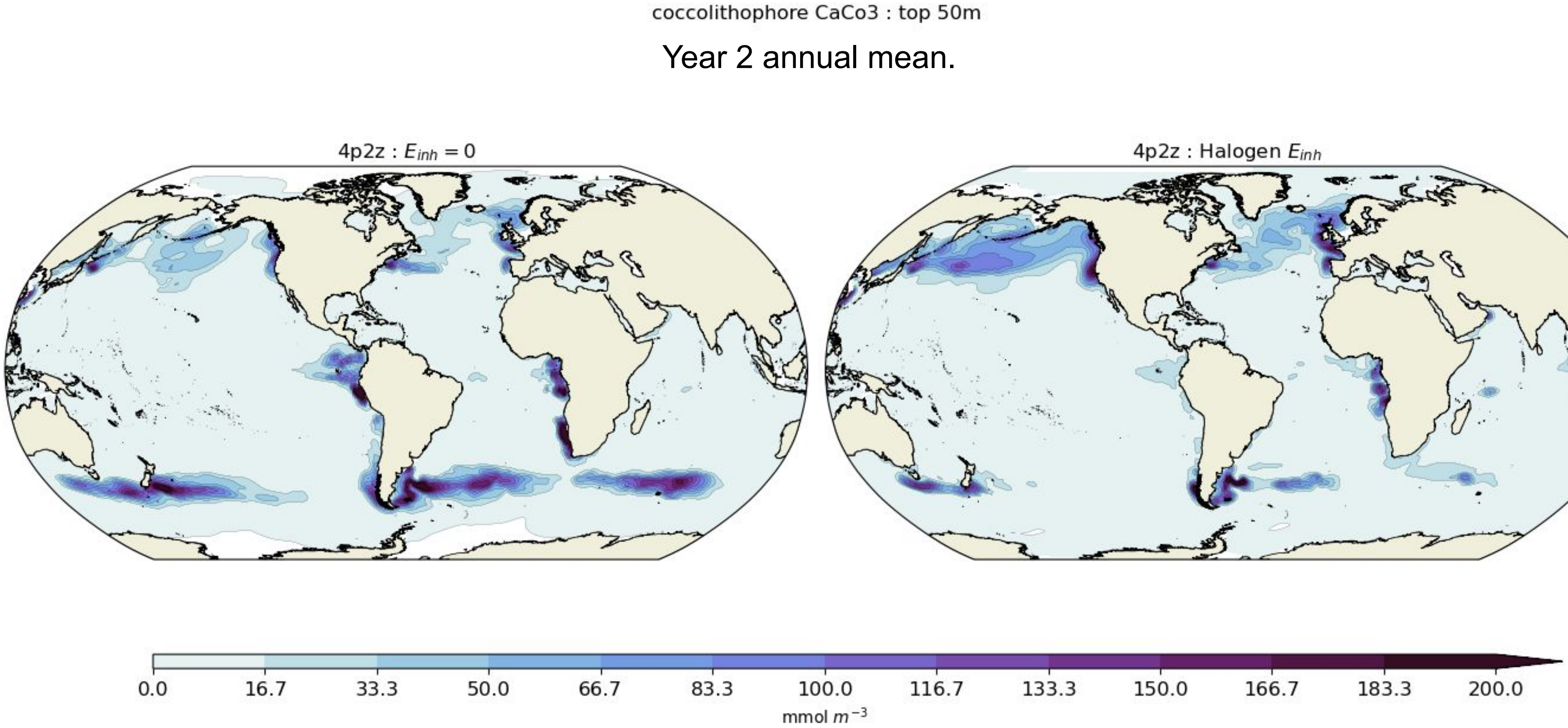


Results [preliminary] - PFT variability

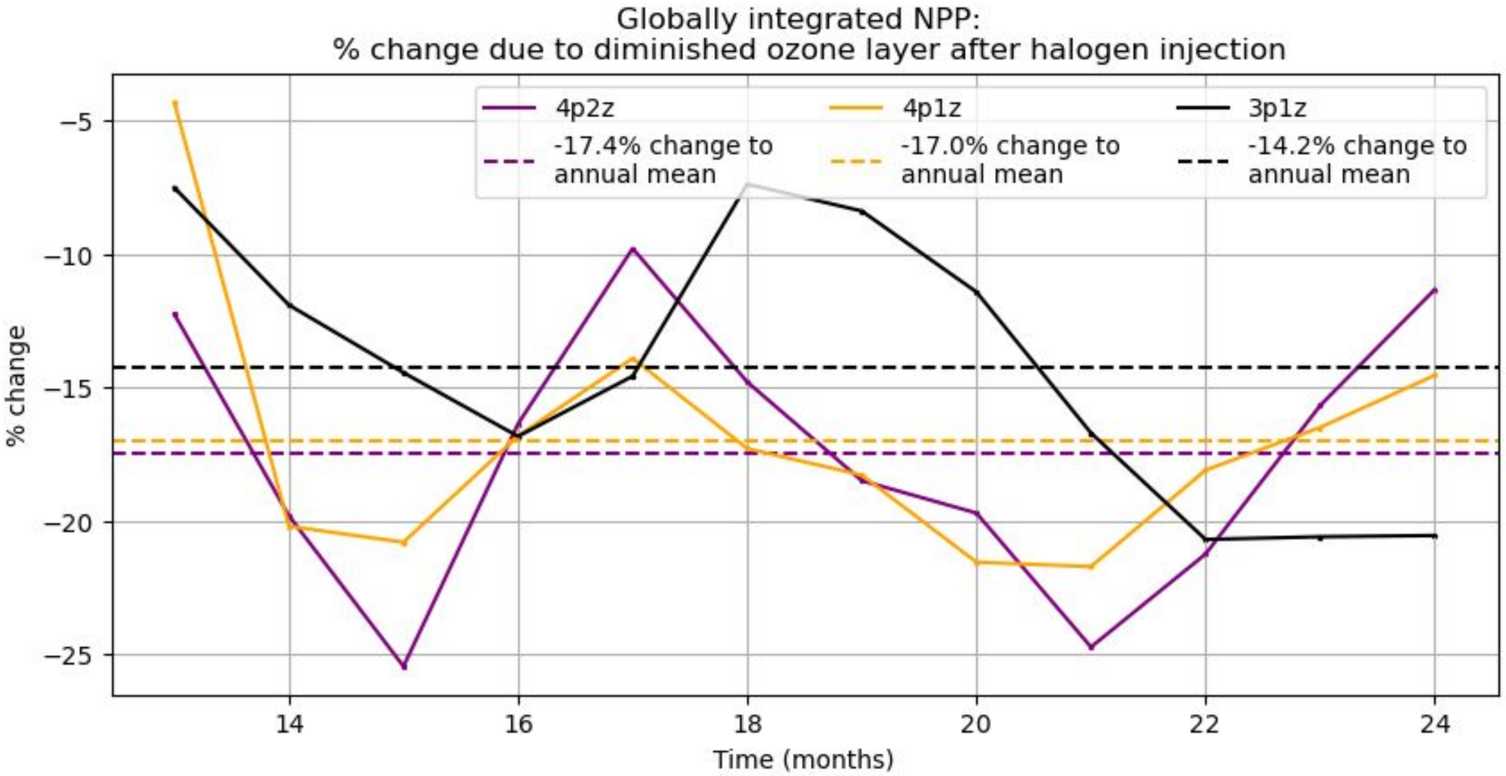
- Variable behavior depending on functional type
  - Diatoms and coccolithophores benefit at the expense of small phytoplankton (usually >50% of all oceanic NPP) and diazotrophs (<10% of all NPP).
  - Diatoms account for ~50% of all NPP, small phytoplankton account for 40% at peak of halogen injection simulation.



Year 2 annual mean.

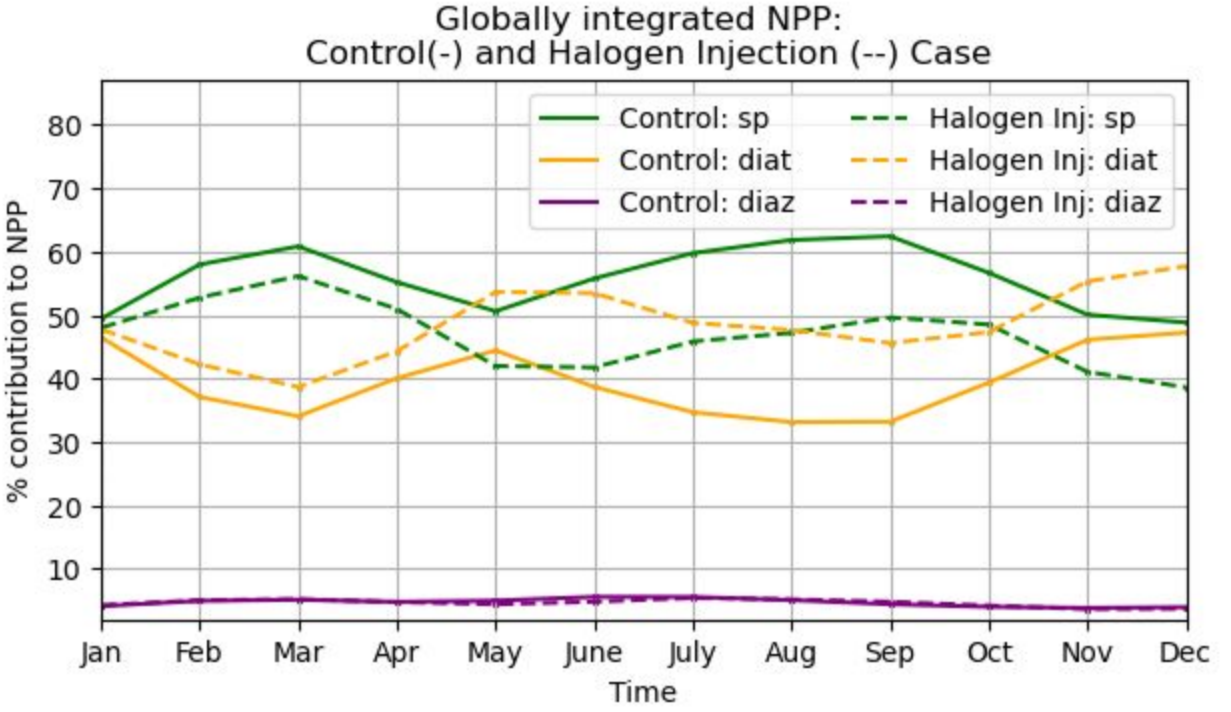


Results [preliminary] - dependence on # of PFT/zooplankton



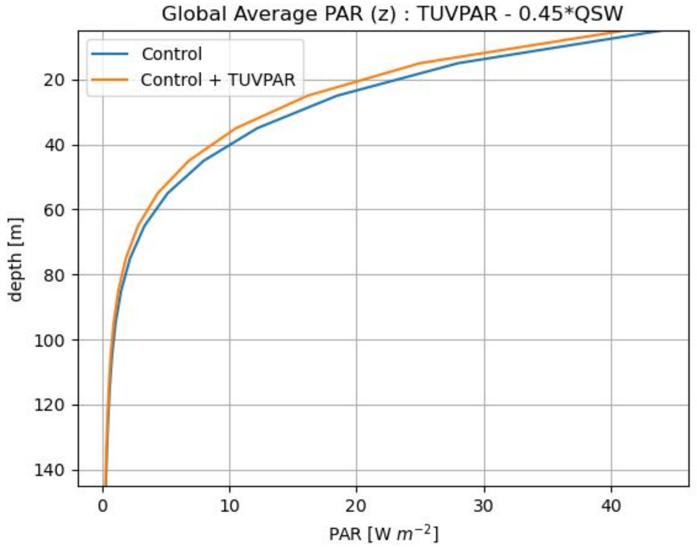
Results [preliminary] - PFT dependence

- The contribution



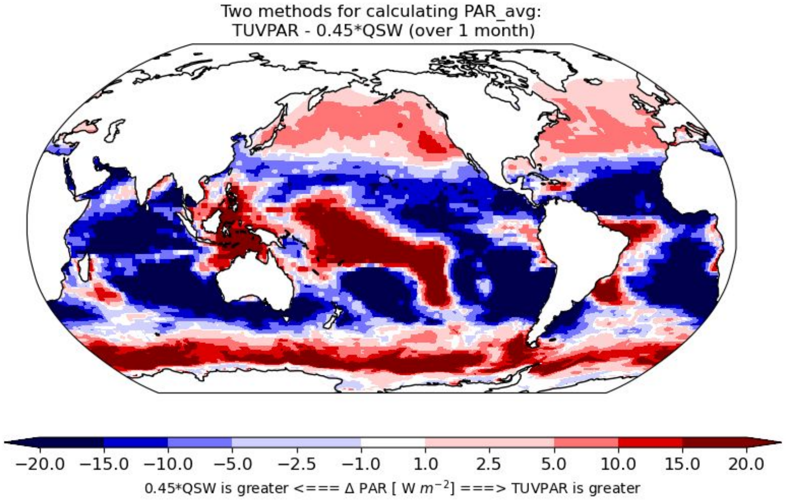
Results - TUVPAR

- TUV model also simulates photosynthetically active radiation (PAR, 400-700 nm), which can be passed to the ocean model.
- MARBL currently assumes PAR is equal to 0.45 * QSW
  - QSW is shortwave radiation received at the surface from the atmosphere.
- TUVPAR reduces PAR compared to old method.



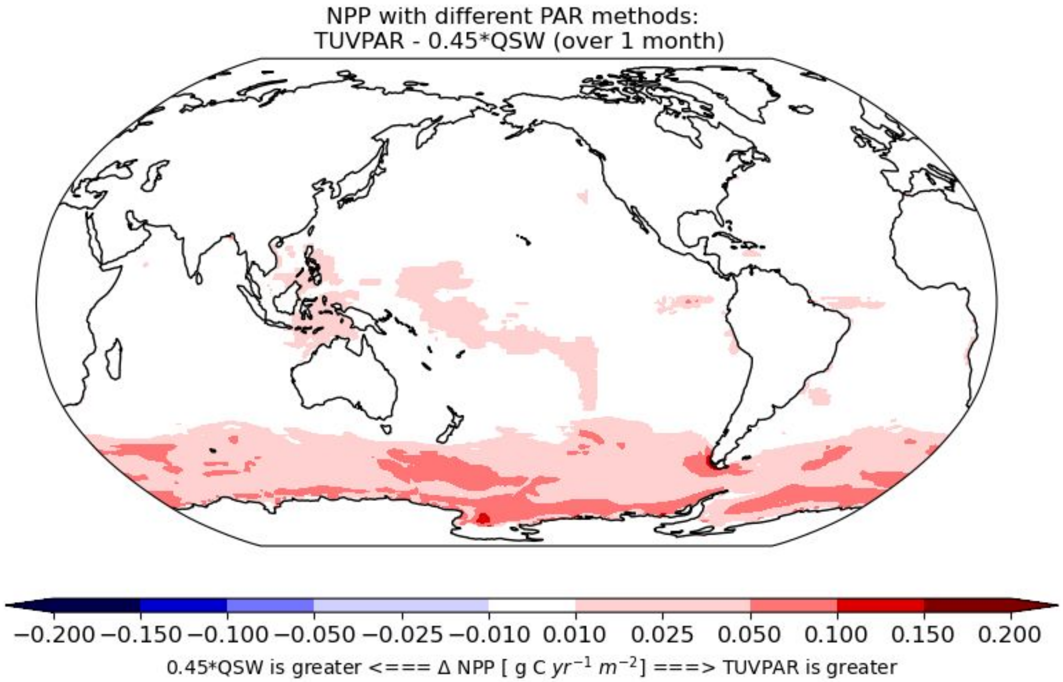
Results - TUVPAR

- TUV model also simulates photosynthetically active radiation (PAR, 400-700 nm), which can be passed to the ocean model.
- MARBL currently assumes PAR is equal to 0.45 * QSW
  - QSW is shortwave radiation received at the surface from the atmosphere.
- TUVPAR reduces PAR compared to old method.



Results - TUVPAR

- TUVPAR causes increased productivity during summer at high latitudes.
    - 10 Pg C yr^{-1} increase in global NPP.
- Sensitivity to different radiation was somewhat expected, but the simulated 20% increase led us to stop using TUVPAR. (for now)



Conclusions

- Low sensitivity to pre-industrial UV radiation in 4p2z
  - Response across 3p1z and 4p1z varies but not significantly.
- Global NPP is somewhat resilient to increased surface UV radiation as phytoplankton communities below 25m thrive at the expense of those closer to the surface.
- Still in somewhat early stages of development, so testing is ongoing.

Future work and potential applications

- Adding in damage functions for coccolithophores as a function of shell thickness:
  - calcium carbonate shells can offer protection from UV-B
  - damage function can be modified as a function of shell thickness
- Is enhanced surface UV radiation after the smoke clears from an asteroid impact a potential mechanism for phytoplankton extinction?
- How will ocean warming and acidification increase susceptibility of phytoplankton to UV radiation?
  - acidification may make it more difficult to form shells
  - increased stratification from warming may trap phytoplankton in areas closer to the surface with higher UV radiation.