Sunburned phytoplankton: Chicxulub asteroid impact as a case study for ultraviolet radiation inhibition in MARBL

Joshua Coupe

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Paleoclimate Working Group 6/12/24

Motivations

- The Chicxulub asteroid impact likely caused a **mass extinction event** at the K-Pg Boundary 66 million years ago.
- The impact caused soot, dust, among other aerosols to enter the upper atmosphere, blocking sunlight and destroying stratospheric ozone.
- The role of ultraviolet (**UV**) radiation has been hypothesized to contribute to extinction.

Here, we use **CESM2-UVphyto** to investigate how phytoplankton evolve post-impact with enhanced UV radiation.

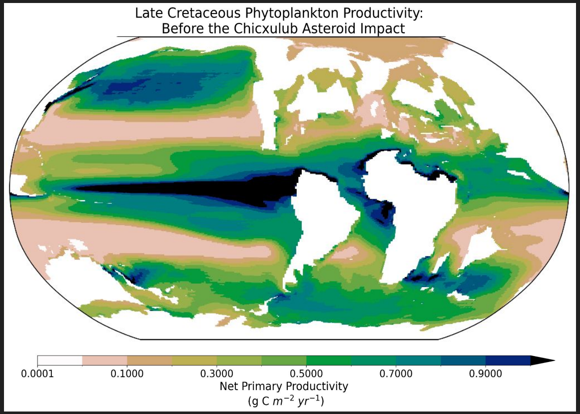
Methods: Ocean model

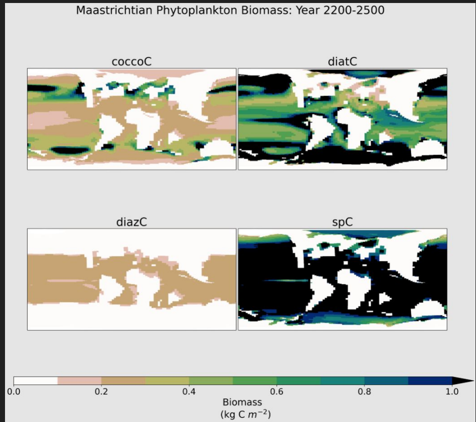
We developed "**CESM2-UVphyto**" with the following components and modifications:

- Ocean: POP2 (Danabasoglu et al., 2012) coupled to the MARine Biogeochemistry Library (MARBL, Long et al., 2021).
    - includes 4 phytoplankton functional types (small phytoplankton, diatoms, coccolithophores, diazotrophs) and 1 zooplankton functional types.
    - simulates biogeochemical response to climatic extremes.
    - 1 degree resolution, 60 vertical levels.

Methods: Model spin-up

- Physical ocean state was spun-up for 1000 years.
  - CAM4 at 1.9 deg x 2.5 deg horizontal resolution used as atmospheric component for spin-up.
- Biogeochemical ocean state was spun-up for 1500 years.
  - initialized using pre-industrial global average values (uniformly distributed).
  - physical state initialized using end of physical spin-up.
  - O_2 consumption was scaled down below 800 m to prevent deoxygenation at depth.
- Continents and boundary conditions set to mimic late Maastrichtian:
  - CO_2 is 850 ppm.
  - CH_4 is 2400 ppb.
  - N_2O is 375 ppb.
  - Solar constant is 1357 W m^{-2}.
  - Global average SSTs are 26°C.





Methods: Atmospheric model

- Atmosphere: WACCM4 (Gettelman et al., 2019) coupled to the Tropospheric Ultraviolet and Visible (TUV) model version 4.2 (Madronich et al., 1997).
  - used to simulate chemical, physical, and radiative consequences of aerosol injections into the stratosphere.
  - computes surface UV-A, UV-B, and UV-C radiation.
- UV damage calculated using biological weighting functions that represent cell damage as a function of wavelength.

$$E^*_{inh} = \sum_{\lambda=280nm}^{400} E(\lambda) \cdot \epsilon(\lambda) \cdot \Delta\lambda,$$

Methods: Biological weighting functions

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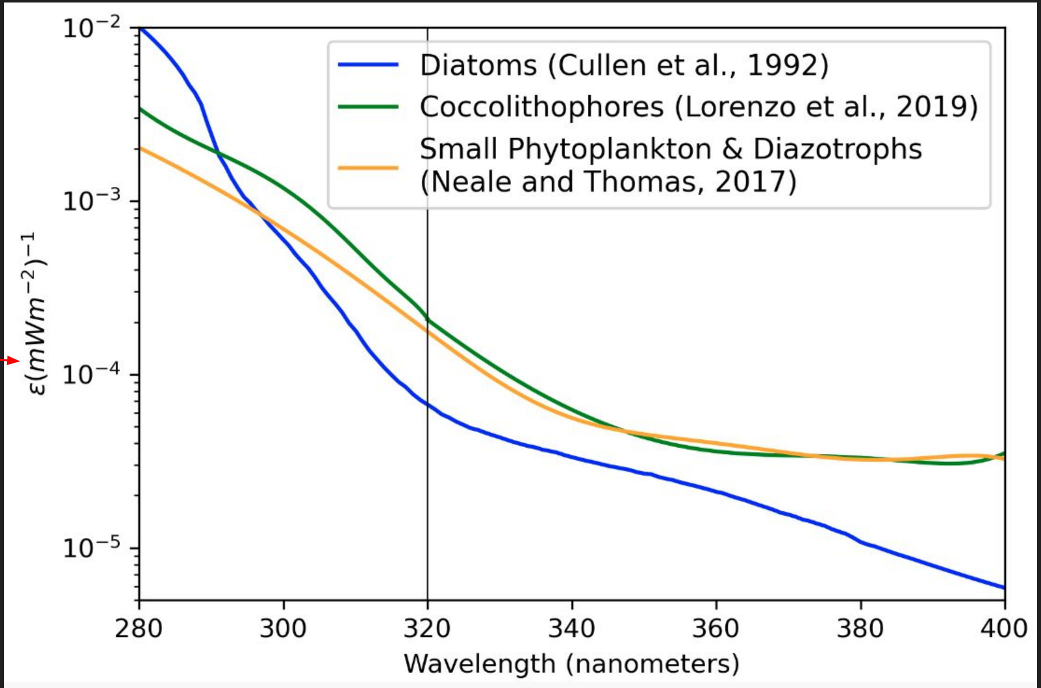
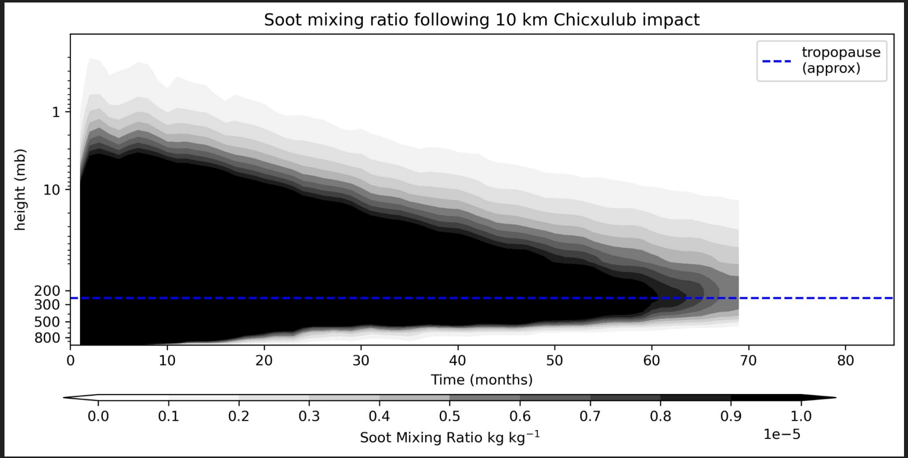


Methods: Asteroid impact simulation

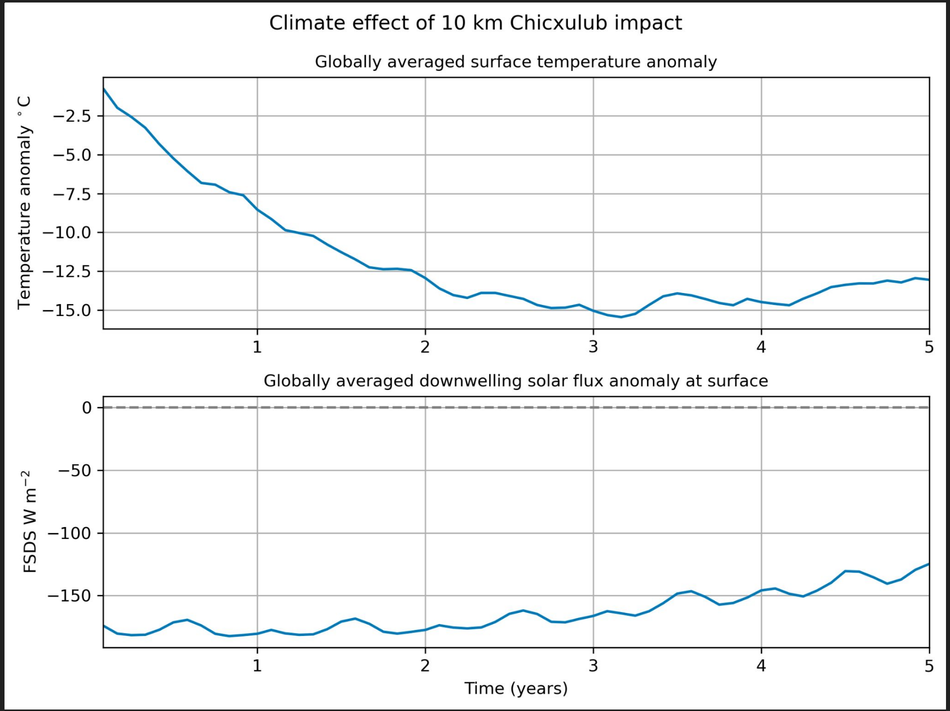
- Emissions based on Toon et al. (2016) and Tabor et al. (2020).
  - Ballistic: globally uniform, centered at 50 km and half-width of one atmospheric scale height.
  - Fire: emission at the surface only over land, scaled by local vegetation density.
  - Splash: mixed uniformly above tropopause with 4000 km radius around impact site.
- Various aerosols and gases injected on Jan 1st.
  - 72,700 total soot (~20,800 Tg fine soot at tropopause)
  - 2,000,000 Tg total dust (ballistic)
  - 117,447 Tg of HBr and HCl (ballistic, fire, and splash)
  - 66,320 Tg NOx emissions (mostly splash and impact, some fire)
  - 7,210,000 H_2O (mostly splash and fire)

Results: Impact winter caused by smoke

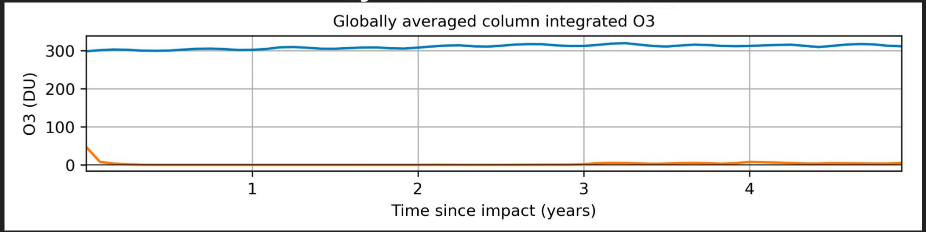
Soot injection



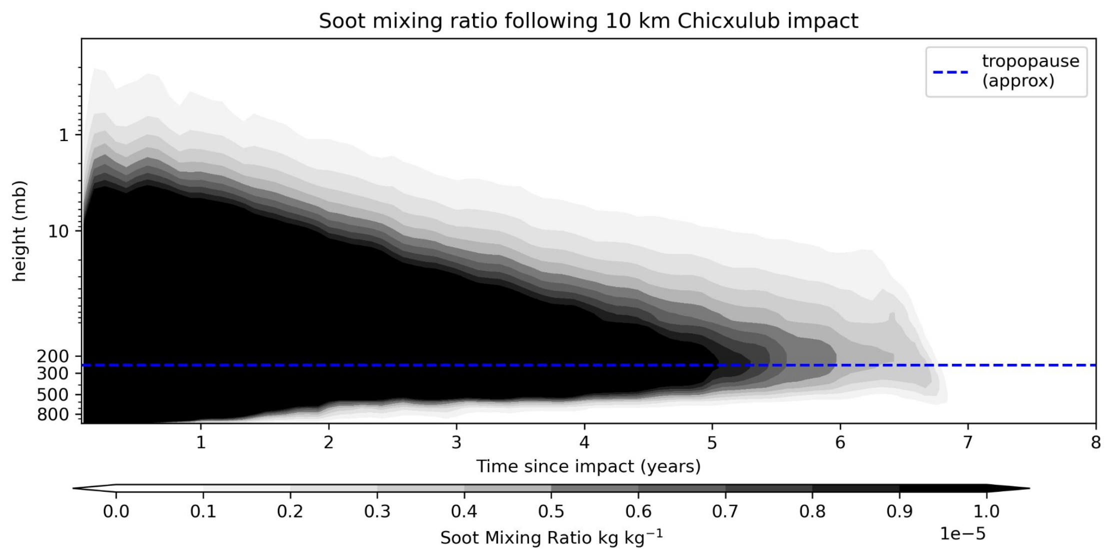
Reduced sunlight and impact winter



Ozone layer destruction

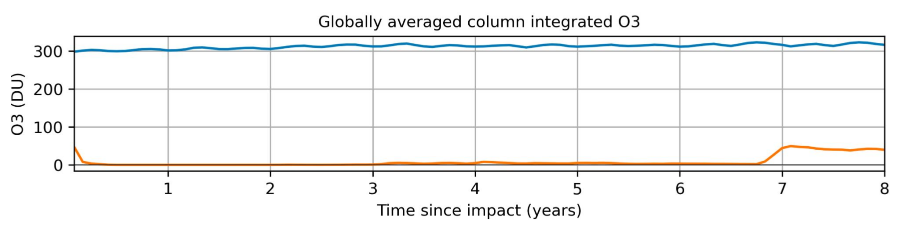


Results: Impact winter caused primarily by soot

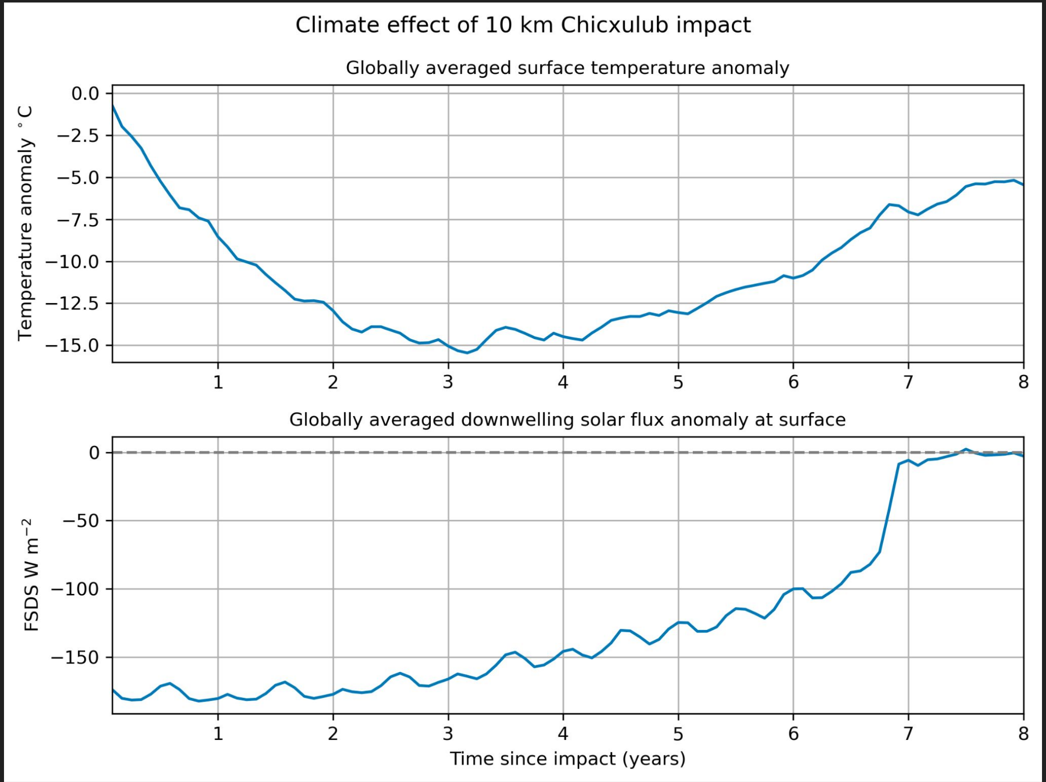


Soot injection visualized as globally averaged vertical profile with time

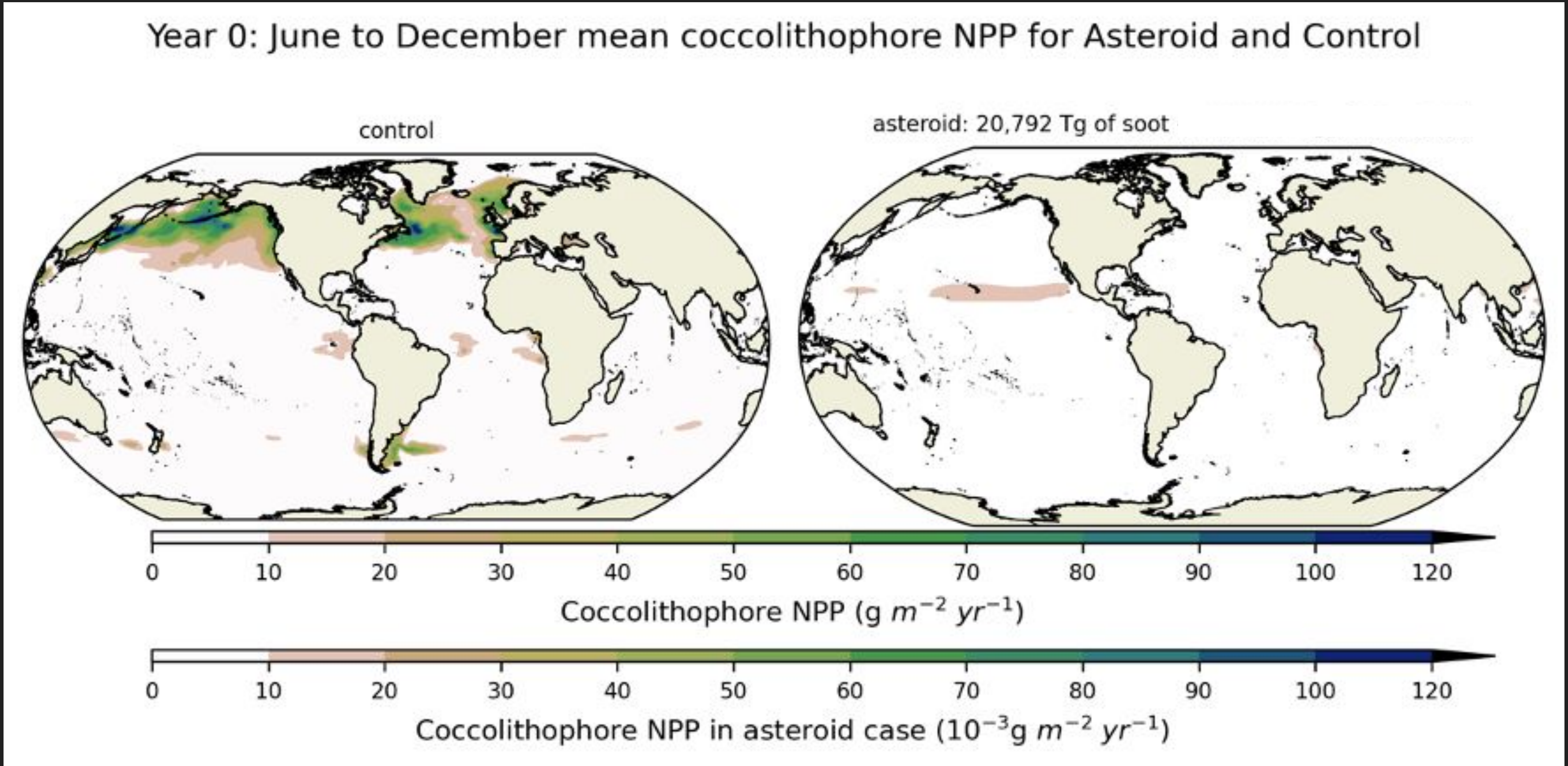
Ozone layer destruction



Results: Impact winter caused by smoke

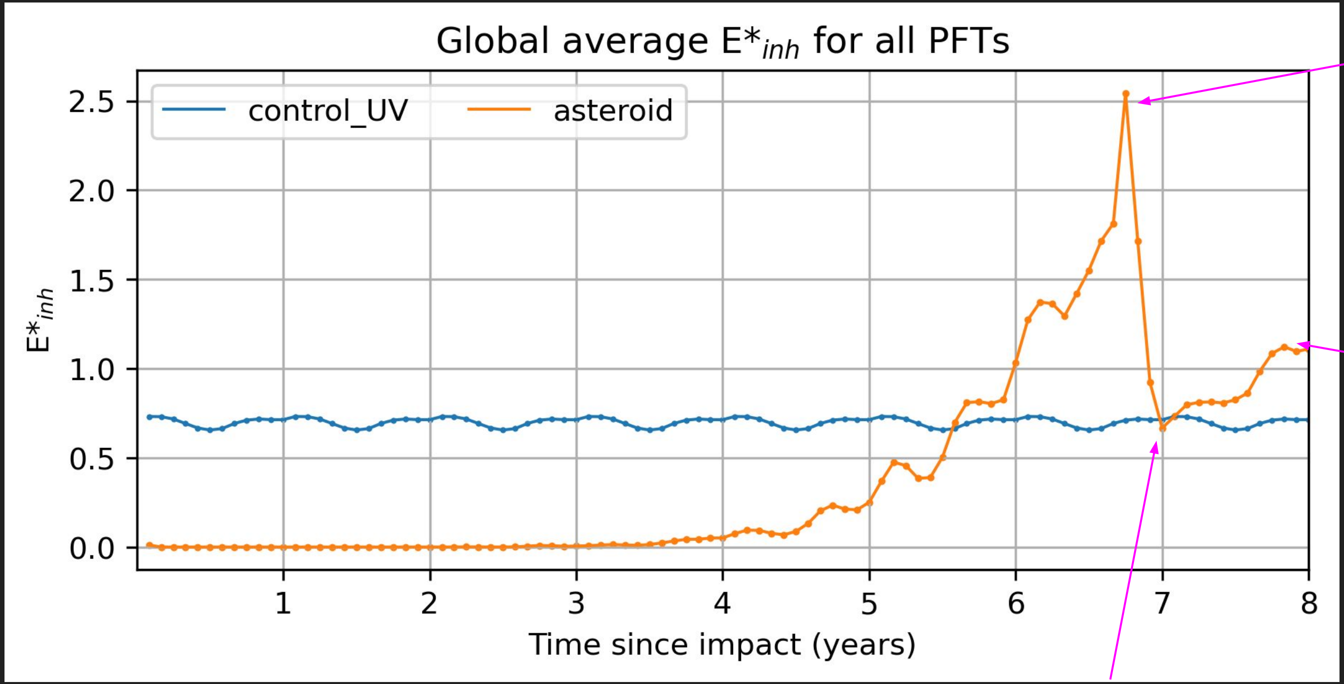


Sunlight is reduced for 7 years, causing impact winter with peak cooling of -15°C.



Year 0: June to December mean coccolithophore NPP for Asteroid and Control
control
asteroid: 20,792 Tg of soot
0 10 20 30 40 50 60 70 80 90 100 120
Coccolithophore NPP (g m^{-2} yr^{-1})
0 10 20 30 40 50 60 70 80 90 100 120
Coccolithophore NPP in asteroid case (10^{-3}g m^{-2} yr^{-1})

Results: UV and E*inh increases ~4 years post-impact

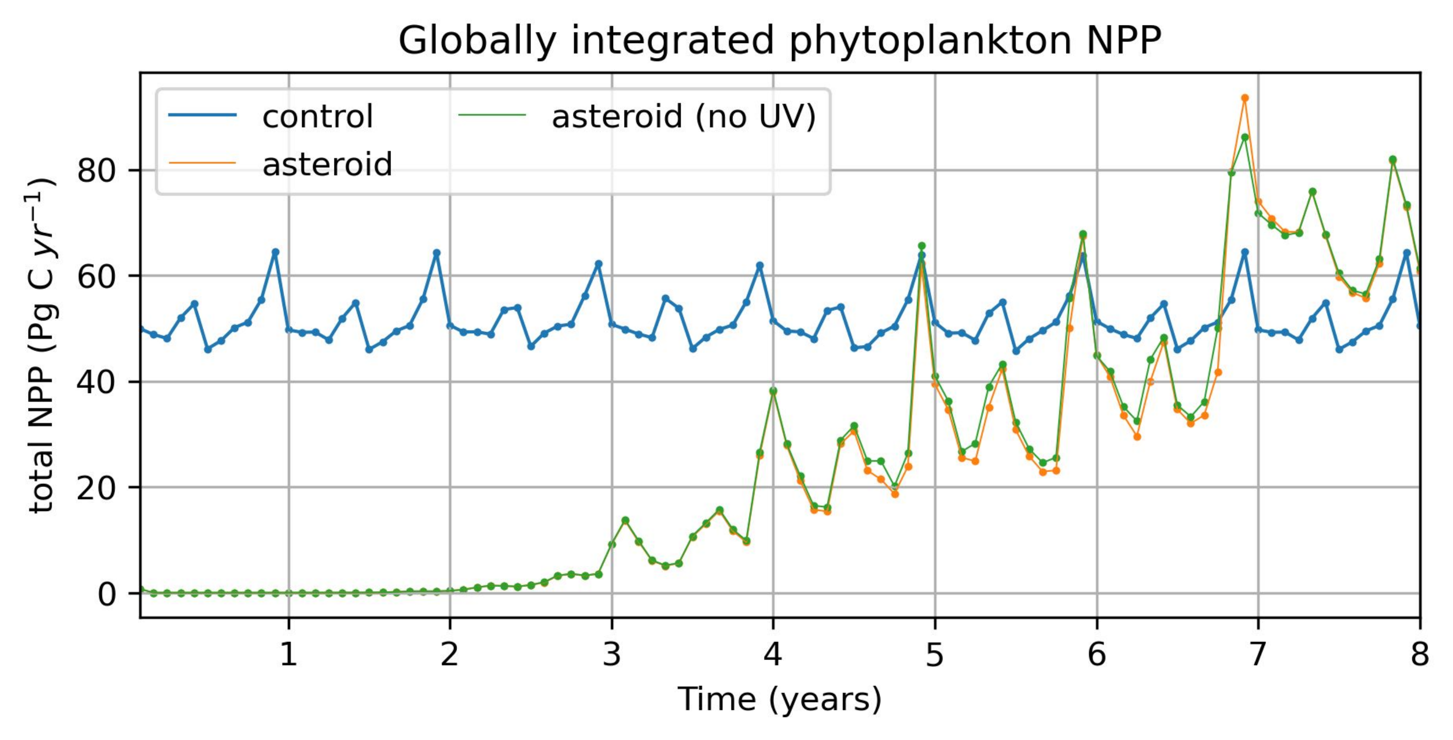


First increase driven by diatom damage.

UV light between 290 nm and 310 nm increase with insolation, other 3 PFTs damage increases.

Diatom damage declines as light between 280 nm - 290 nm is filtered by small increase in O_3 .

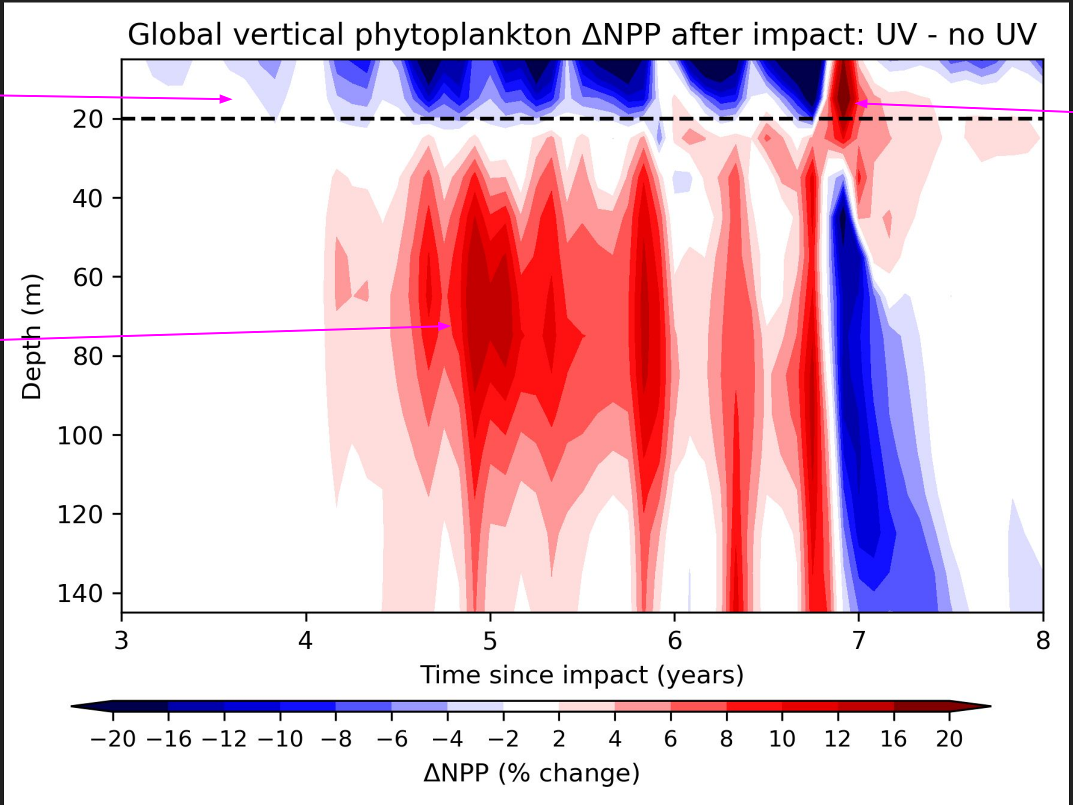
Results: Impact winter drives severe decline in total phytoplankton productivity



Results: UV radiation drastically shifts vertical distribution of productivity post-impact

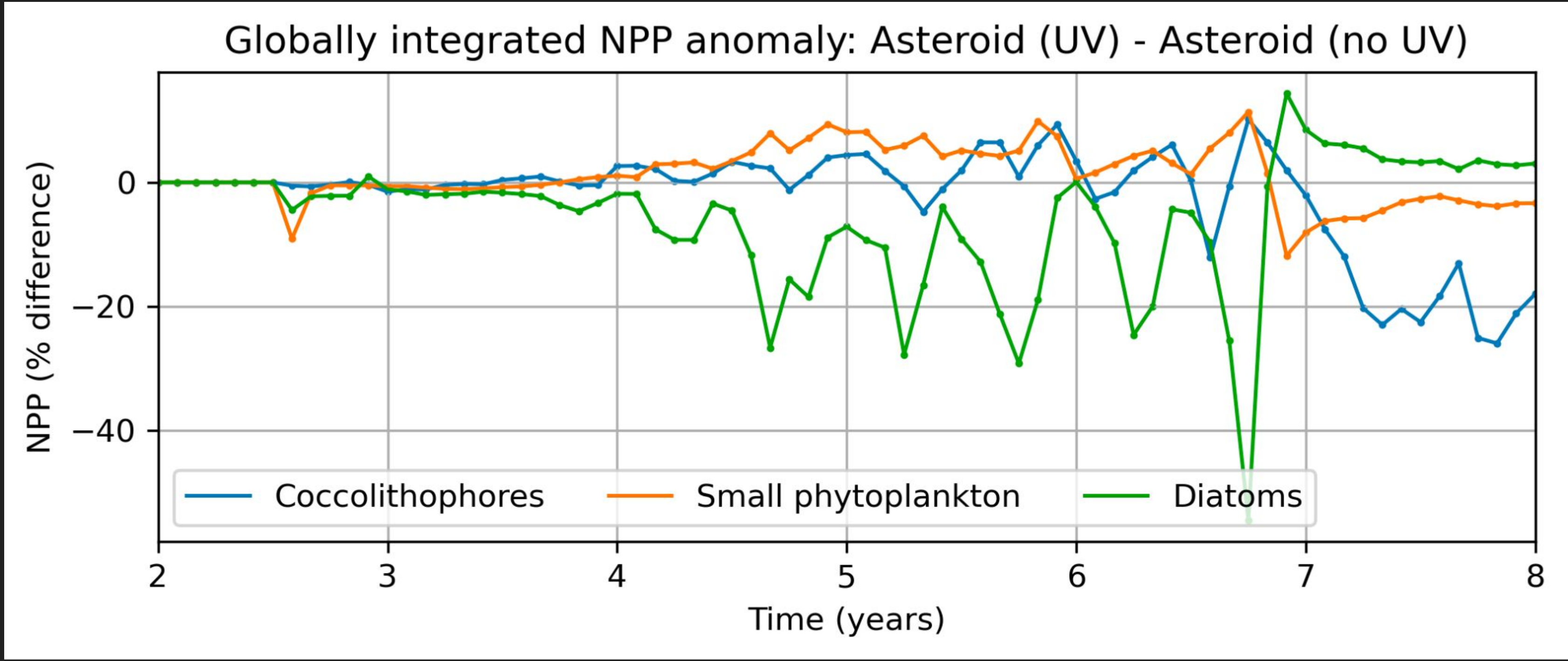
Expected decline in top ~15 m.

Unexpectedly strong compensation at depth from reduced shading.



Decline in diatom damage accompanied by sudden increase in productivity, then increased shading at depth!

Results: Post-impact UV spike impacts the phytoplankton types differently



Conclusions

- Proof of concept simulations show evidence of a post-impact UV spike which can influence marine phytoplankton.
- In the first 8 years after impact, UV levels not a major factor.
- If stratospheric ozone was slow to recover, UV radiation may have shape the vertical profile of productivity.

Summary

- CESM2-UVphyto requires modifications to atmosphere, coupler, ocean, and ocean biogeochemistry models.
- Simulates minimal response to PI UV radiation, moderate response to enhanced UV radiation.
- Manuscript describing model modifications has been submitted to Geoscientific Model Development.

Sunburned plankton: Ultraviolet radiation inhibition of phytoplankton photosynthesis in the Community Earth System Model version 2

Joshua Coupe[1,2], Nicole S. Lovenduski[1,2], Luise S. Gleason[3], Michael N. Levy[4], Kristen Krumhardt[4], Keith Lindsay[4], Charles Bardeen[5], Clay Tabor[6], Cheryl Harrison[7], Kenneth G. MacLeod[8], Siddhartha Mitra[9,10], and Julio Sepúlveda[2,11]