Modeling the Impacts of Water Quality on SAV and other Living Resources in the Tidal Chesapeake Bay

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Motivation for this work:

Basic:

- Link hydrologic optics with physiology to develop fundamental understanding of climate impacts on aquatic photosynthesis

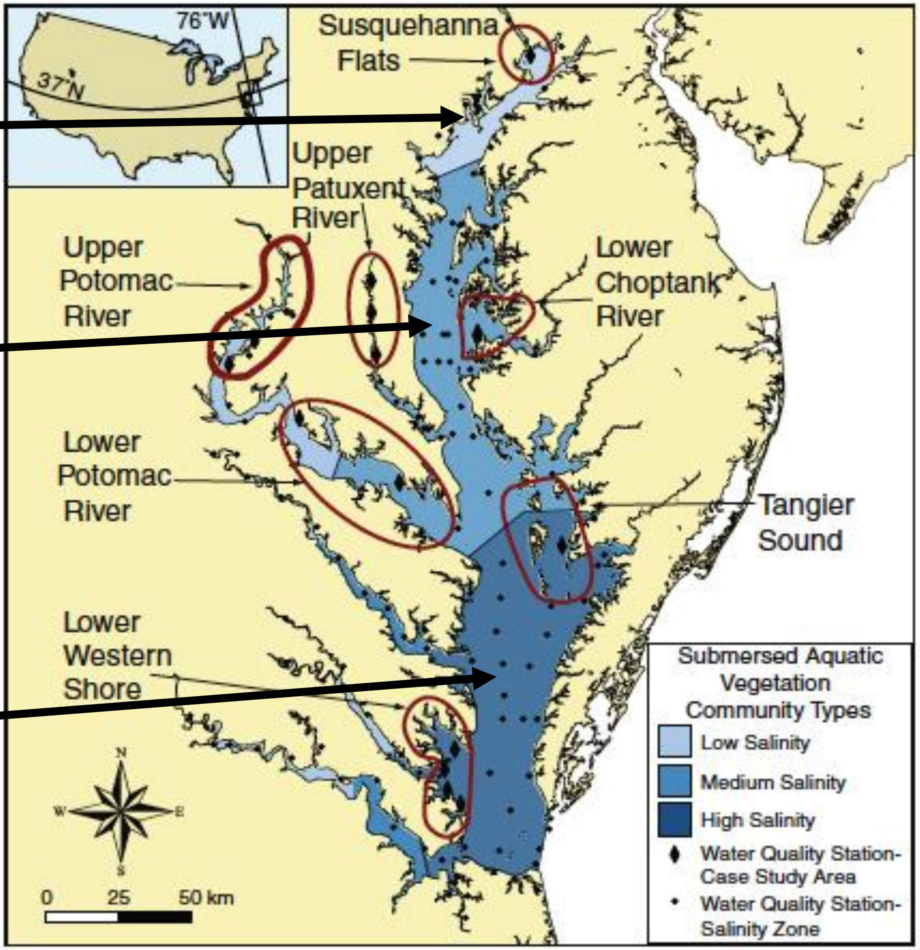
Applied:

- Improve our ability to model & manage the impacts of water quality on shallow water resources in the Chesapeake Bay
  - Existing Bay Model works well in the main stem of the Bay but fails to predict WQ and SAV distributions in shallow water, esp tributaries

Part A: Modeling light limited distribution of SAV

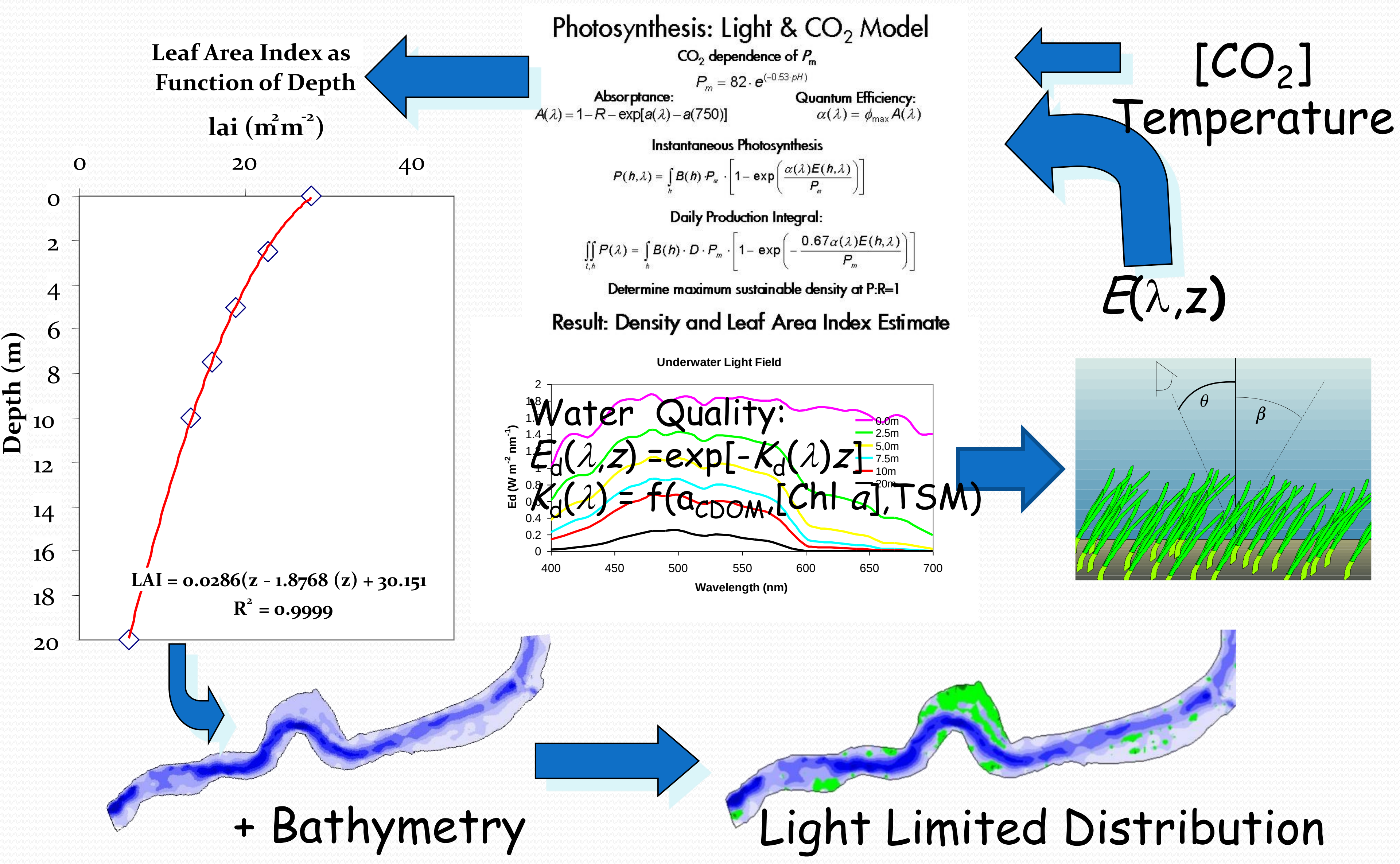
Salinity controls SAV community structure

- 3 Broad Salinity regimes
- Oligohaline
  - Salinity <5 (PSS)
  - Fresh water habitat
- Mesohaline
  - 5 to 15 (PSS)
  - Highly variable
  - Most affected by dry/wet rainfall patterns
- Polyhaline
  - Salinity >15 (PSS)
  - Southern Bay
  - Mostly marine habitat



Map by R. J. Orth, VIMS

Predicting SAV Distributions: Grasslight



Applying *GrassLight* to the Chester River

- Mesohaline near the mouth
- Oligohaline to fresh in the upper reaches
- Highly turbid
  - TSM » 30 mg L^{-1}
- Eutrophic
  - Chl *a* » 20 mg m^{-3}

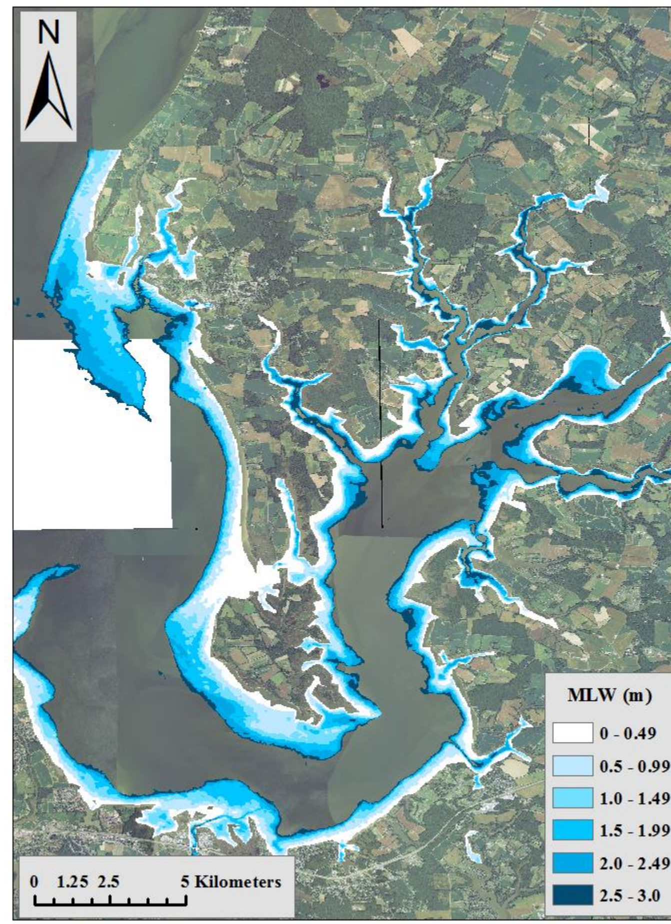
Chester River Potential SAV Habitat

Imagery from Geospatial Data Gateway; 2013 National Ag. Imagery Program Mosaic

Applying *GrassLight* to the Chester River

- Mesohaline tributary
- Highly turbid
  - TSM » 30 mg L^{-1}
- Eutrophic
  - Chl *a* » 20 mg m^{-3}
- Gridded 30 m bathymetry
- Potential SAV habitat (< 3 m depth) fringing the shore

Chester River DEM

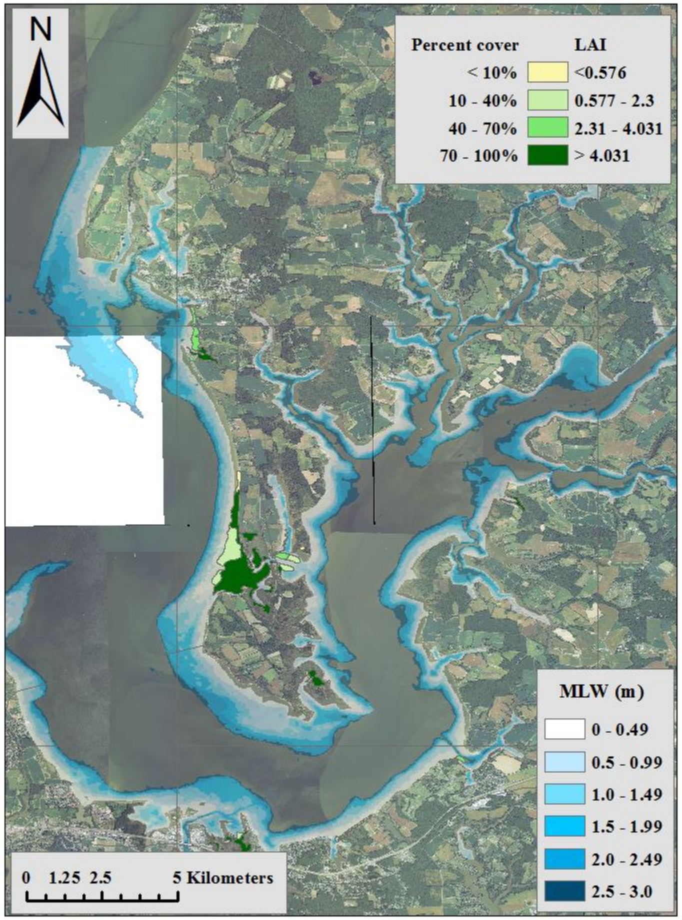


Imagery from Geospatial Data Gateway; 2013 National Ag. Imagery Program Mosaic

Applying *GrassLight* to the Chester River

- SAV distribution
  - Most persistent in shallows around Eastern Neck Island and Chester shoreline
  - Species composition depends on salinity
  - Abundance depends on water quality
  - Temporally variable

Chester River VIMS SAV distribution 2011



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Applying *GrassLight* to the Chester River

- SAV distribution
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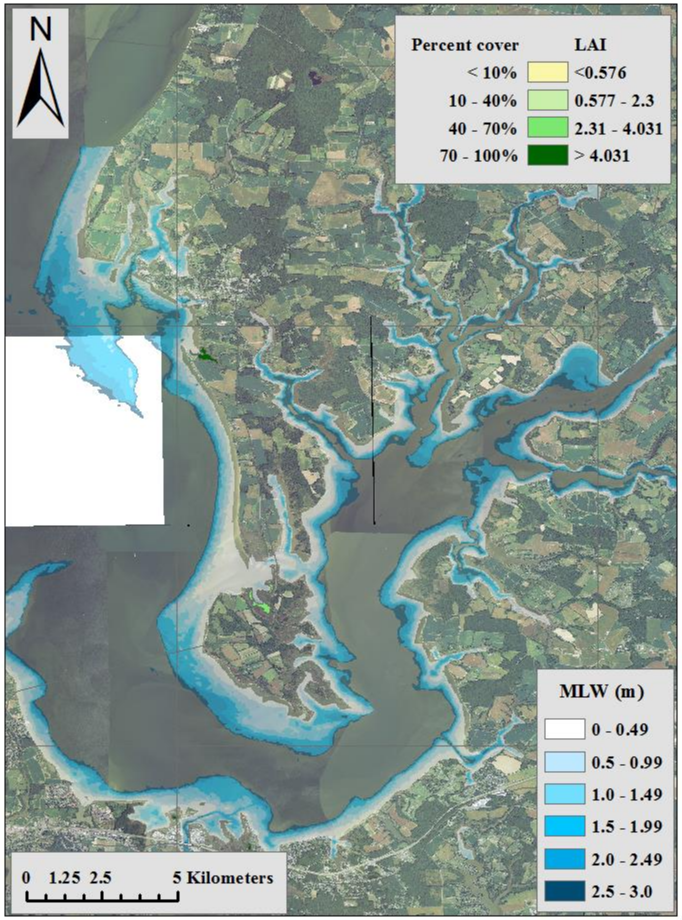
Chester River VIMS SAV distribution 2013

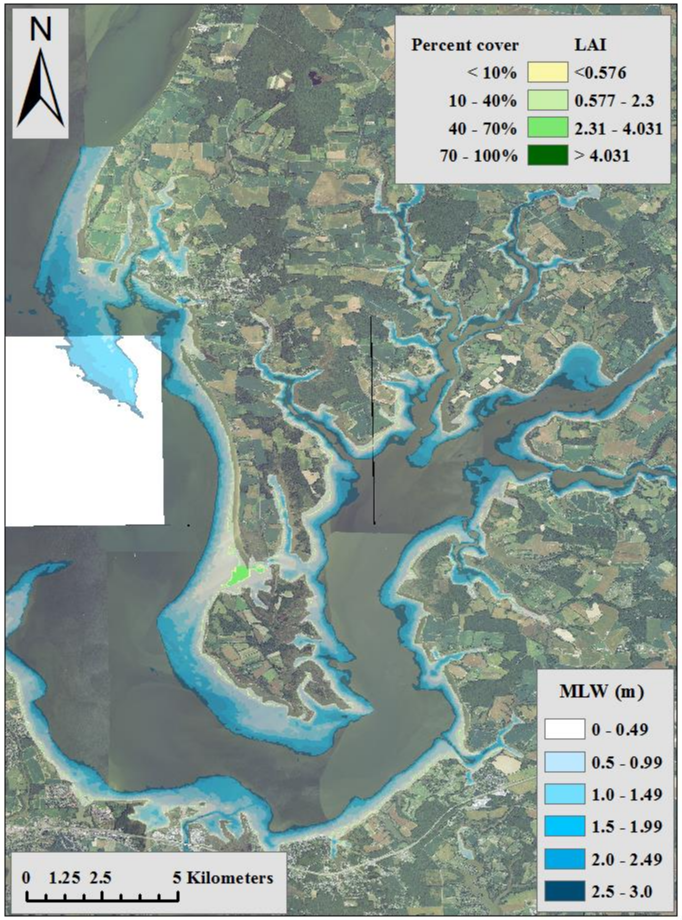


Imagery from Geospatial Data Gateway; 2013 National Ag. Imagery Program Mosaic

Applying *GrassLight* to the Chester River

- GrassLight prediction of SAV density based on average WQ data is consistent with VIMS field observations
- TSM = 30 mg L^{-1}
- Chl *a* = 20 mg m^{-3}
- $z_{E(22\%)}$ = 0.2 m
- $z_{E(13\%)}$ = 0.3 m
- $z_{E(1\%)}$ = 0.8 m

Chester River potential SAV distribution Corsica WQ

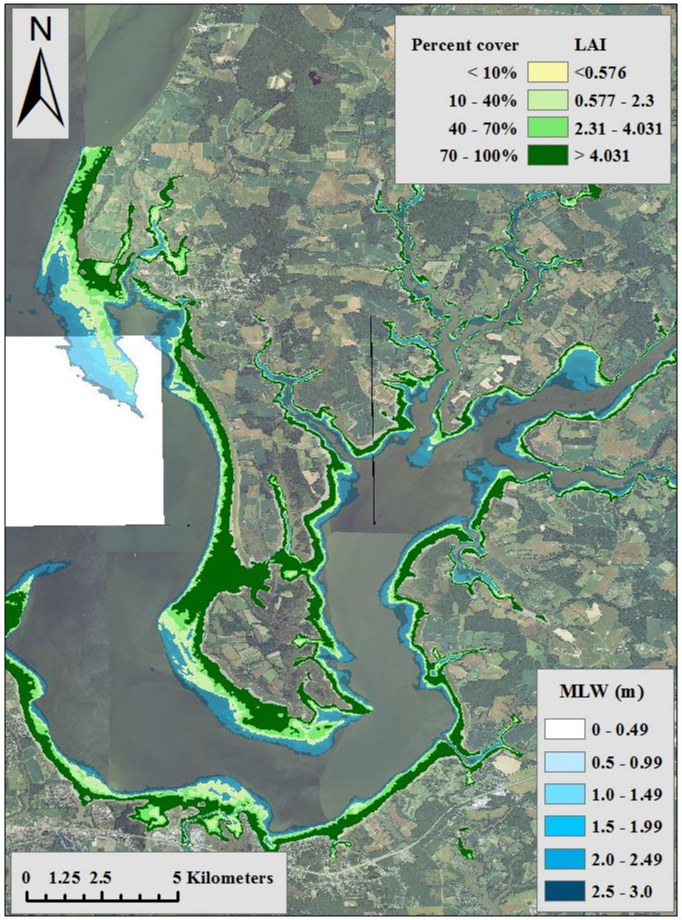


Imagery from Geospatial Data Gateway; 2013 National Ag. Imagery Program Mosaic

Applying *GrassLight* to the Chester River

- Improving water quality to average for Sandy Point
  - TSM = 10 mg L^{-1}
  - Chl *a* = 10 mg m^{-3}
  - $z_{E(22\%)}$ = 0.7 m
  - $z_{E(13\%)}$ = 0.9 m
- SAV distribution expands
- Still below 'historic" distribution limit of 3 m
- Euphotic depth $z_{E(1\%)}$ = 2 m
- So, what about the phytoplankton?

Chester River potential SAV distribution Sandy Pt WQ



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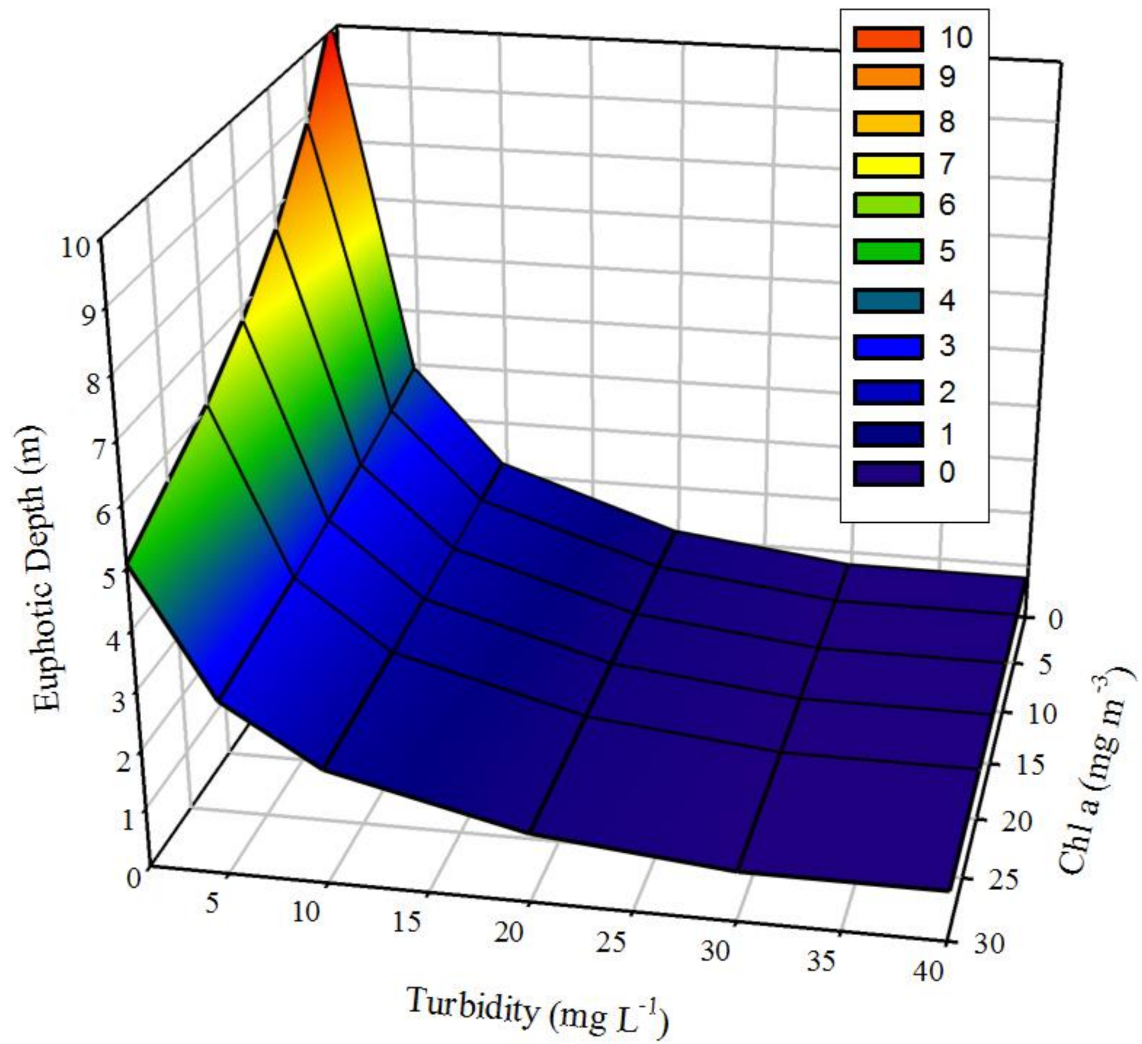
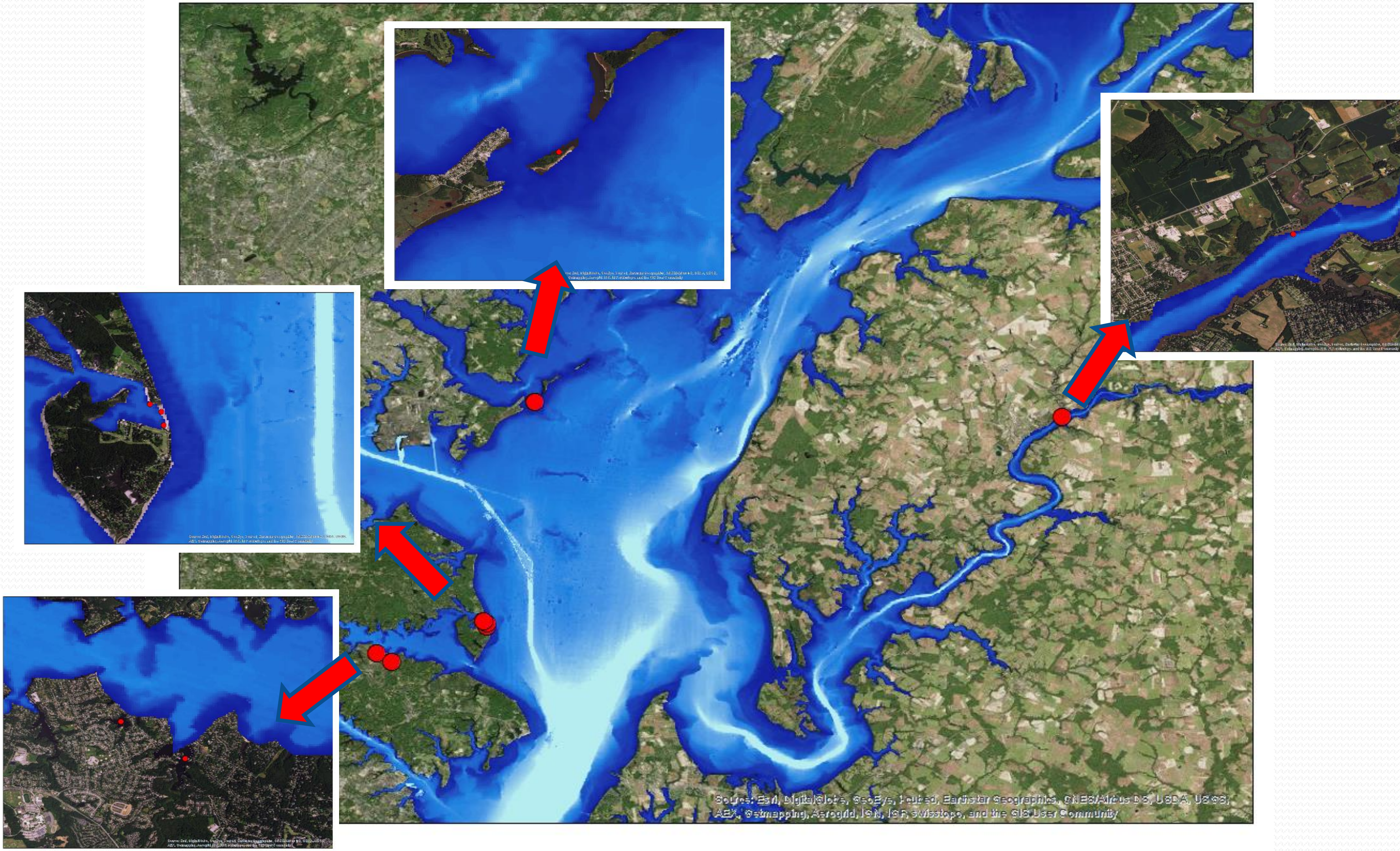
Turbidity has a greater effect on the euphotic depth than Chl *a*



Applying *GrassLight*



Part B: Modeling light limited distribution of phytoplankton

Modeling the plankton component

- Bio-optical components already built into *GrassLight* for given levels of Chl *a*
- Metabolic component required to calculate
  - Gas exchange
  - Nutrient removal & regeneration
  - Algae growth, grazing and sinking
  - Subsequent impact on water transparency

Modeling the plankton component

- The 2-D (depth,time) model:
  - Easily integrated into *GrassLight* bio-optical structure
  - Calculates biologically mediated changes in
    - O2, DIC & therefore pH
    - Dissolved nutrients
  - Ultimately driven by light availability
    - Includes a self-shading component from algal biomass
  - Responsive to nutrient concentrations
    - But does not require explicit definition of Michaelis-Menten coefficients
- It does NOT presently consider
  - Mixotrophic & motile algae (e.g. Dinoflagellates) that exhibit complex behaviors & trophic relations
  - Benthic & pelagic grazing
  - Advection

Modeling the light distribution

- *Spectral availability of light with depth is modeled using*

Water Quality:
$E_d(\lambda, z) = \exp[-K_d(\lambda) z]$
$K_d(\lambda) = f(a_{CDOM}, [\mathrm{Chl}\ a], TSM)$

- *Initializing optical variables are [Chl a], TSM and CDOM*

Modeling the photosynthesis

- P^B_g(z) is controlled by light availability:

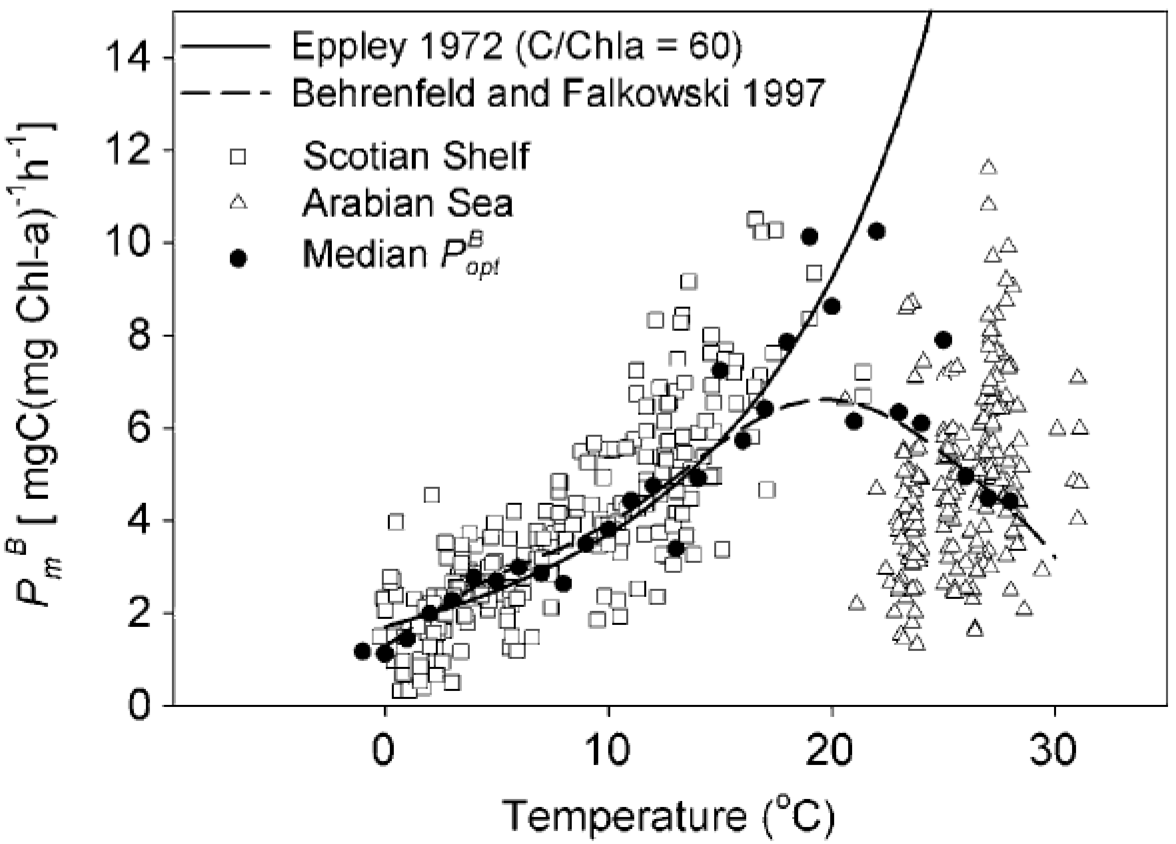
$$P_g^B = P_m^B \left(1 - e^{\frac{\phi_P \cdot A_\phi^*(\lambda) \cdot [\mathrm{Chl}\,a] \cdot E(\lambda,t,z)}{P_m^B}} \right)$$

- ϕ_P – quantum yield of photosynthesis (=1/8)
- $A^*_\phi(\lambda)$ – spectral phytoplankton absorptance
- [Chl *a*] – biomass, to scale absorptance
- $E(\lambda,t,z)$ – wavelength, time and depth-dependent irradiance
- P_m^B - light limited photosynthesis

Modeling temperature effects

$$\log P_E^B \text{ or} \log R^B = T\left(\frac{\log Q_{10}}{10}\right) + C$$

- P_m^B and R are temperature dependent
- Q_{10} = 3 to 20° C
- P_m^B increases up to 20 °C, then
- P_m^B decreases linearly with T to 38° C
- R increases with temp



Bouman, H., T. Platt, S. Sathyendranath, and V. Stuart. 2005. Dependence of light-saturated photosynthesis on temperature and community structure. Deep Sea Research Part I: Oceanographic Research Papers **52: 1284-1299.**

Modeling carbon balance and nutrient requirements

- Net productivity is defined by the balance between photosynthesis and respiration

$$P_{net}^{V} = B\left[P_{g}^{B} - R^{B} \right]$$

- Redfield Ratios define the amounts of dissolved inorganic nitrogen (N) and phosphorus (P) required to convert net photosynthesis into new biomass:

$$\frac{\partial \mathrm{N}}{\partial t} = \frac{16}{106} P_{net}^{V}$$

$$\frac{\partial \mathrm{P}}{\partial t} = \frac{1}{106} P_{net}^{V}$$

Modeling nutrient limitation

- if $\frac{\partial \mathrm{N}}{[\mathrm{N}]} \leq 1$ and $\frac{\partial \mathrm{P}}{[\mathrm{P}]} \leq 1$, phytoplankton growth is defined by

P^{V}_{net} and the concentrations of dissolved inorganic N and P are reduced accordingly

- NH_4^+ taken up before NO_3^-
- If $\frac{\partial \mathrm{N}}{[\mathrm{N}]} > 1$ or $\frac{\partial \mathrm{P}}{[\mathrm{P}]} > 1$, phytoplankton growth is limited by the nutrient in shortest supply, all of which is taken up:

$$\frac{\partial Phyto}{\partial t} = P^{V}_{net} \cdot lesser\,of\,\frac{[\mathrm{N}]}{\partial \mathrm{N}}, \frac{[\mathrm{P}]}{\partial \mathrm{P}}$$

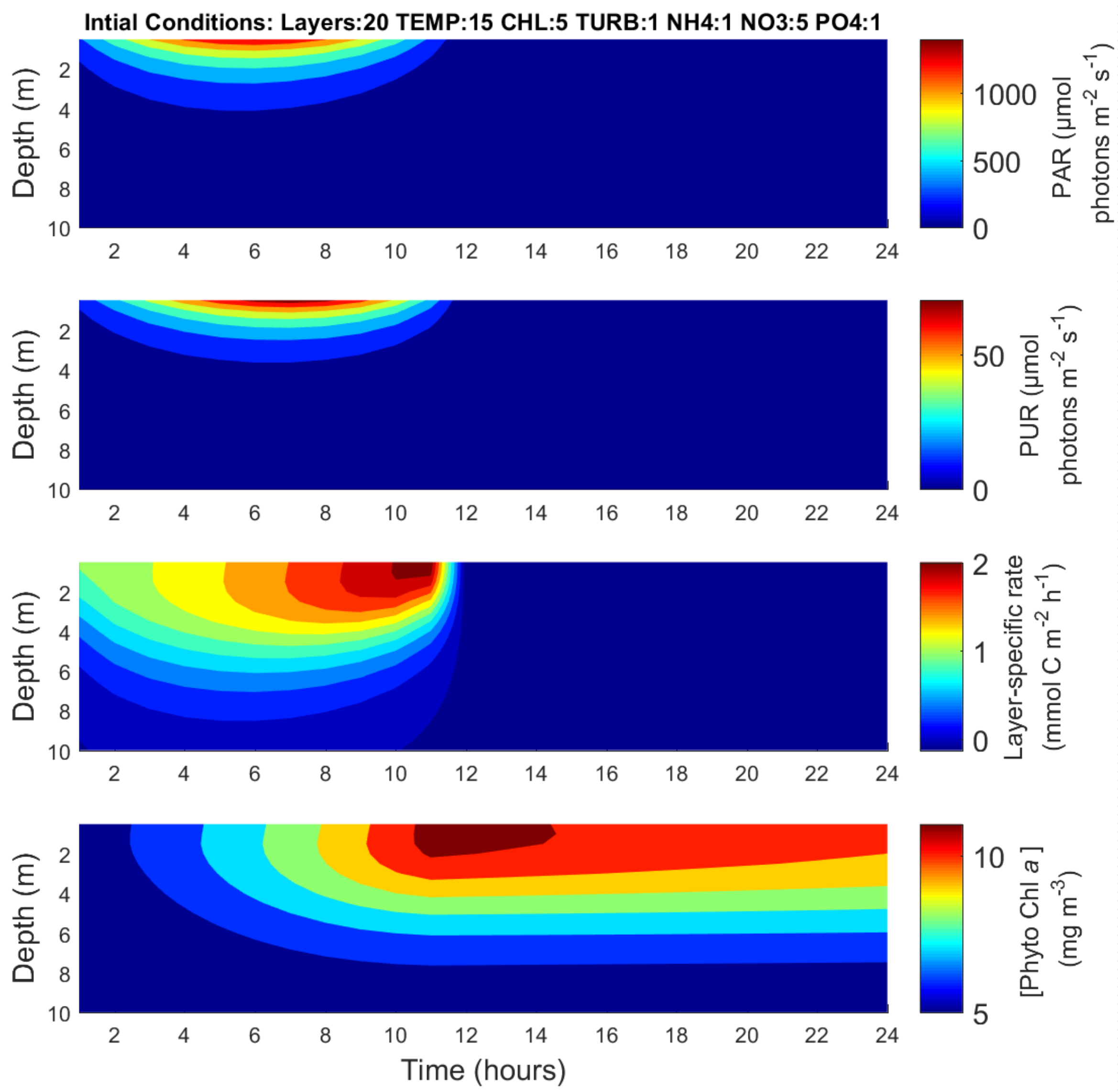
Modeling sinking and diffusion

- Particles are redistributed at the end of each time step via sinking and diffusion.
  - Sinking is set to 0.1 m d^{-1}
  - Diffusion is based on eddy diffusivity coefficient 0.0396 m^2 h^{-1}. Based on vertical gradient in concentration of particles.

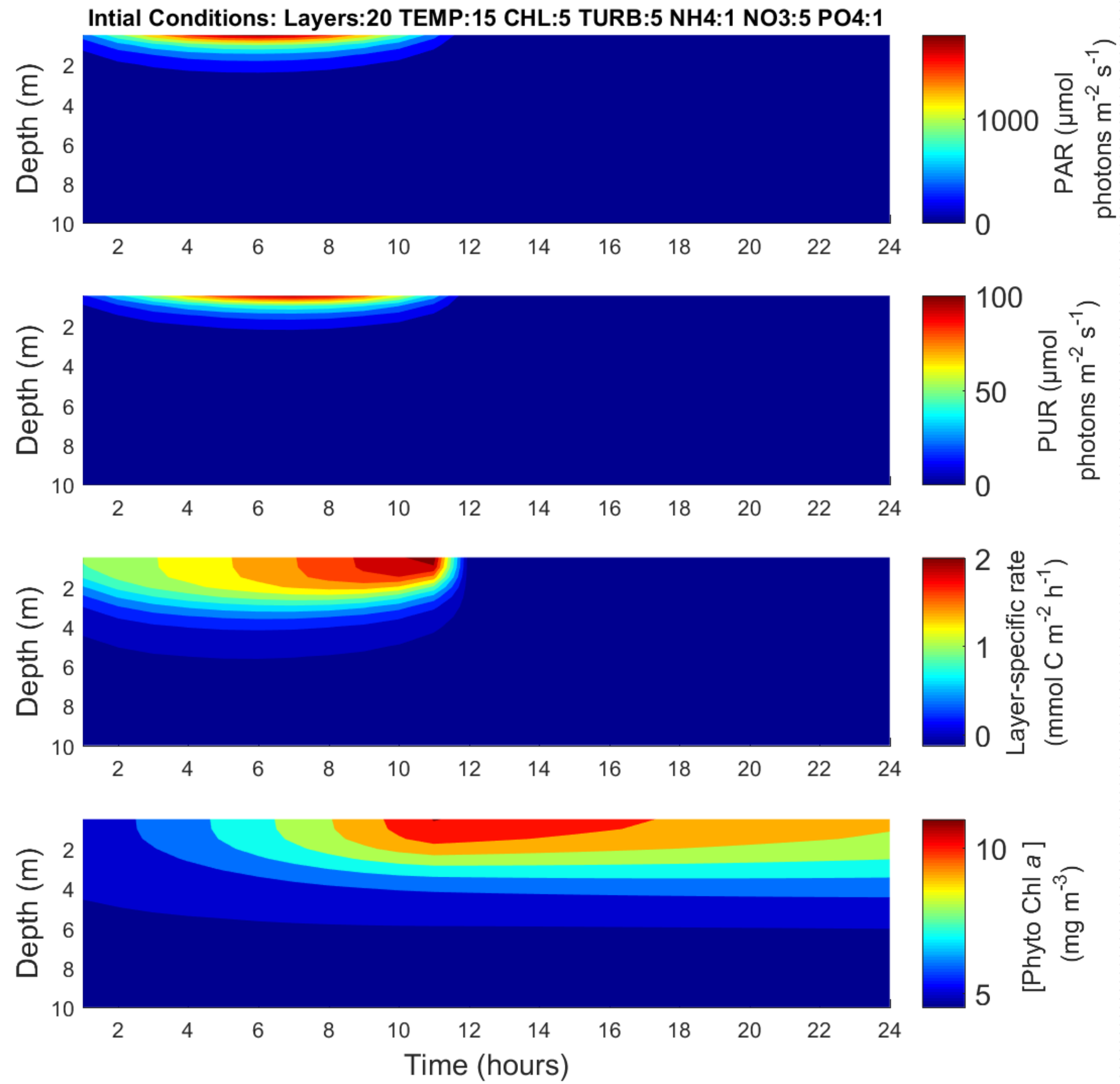
Case 1: Effect of water transparency on phytoplankton productivity

- Chl a will remain constant, TSM will increase.

Effect of water transparency on phytoplankton productivity



Effect of water transparency on phytoplankton productivity



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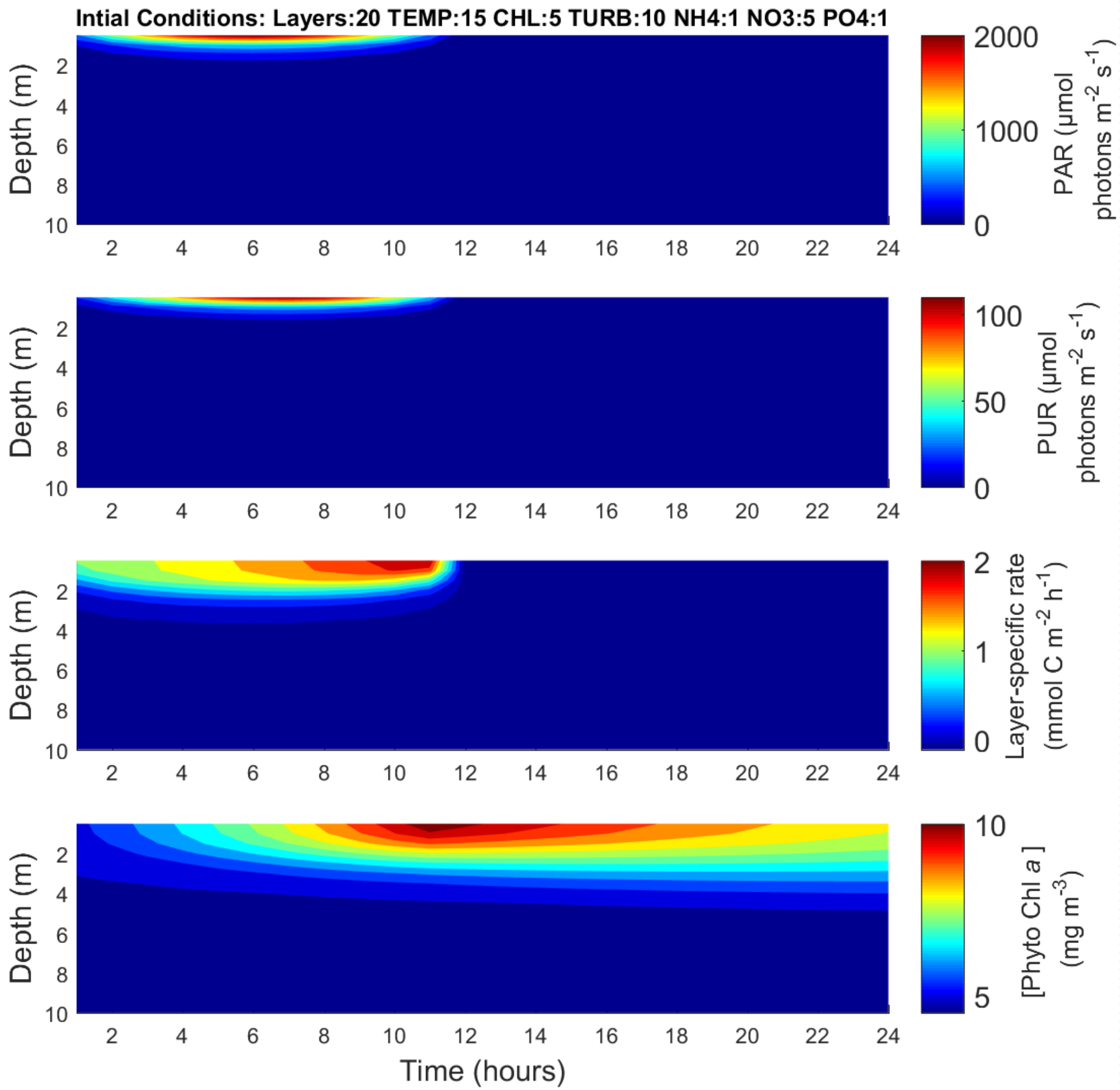

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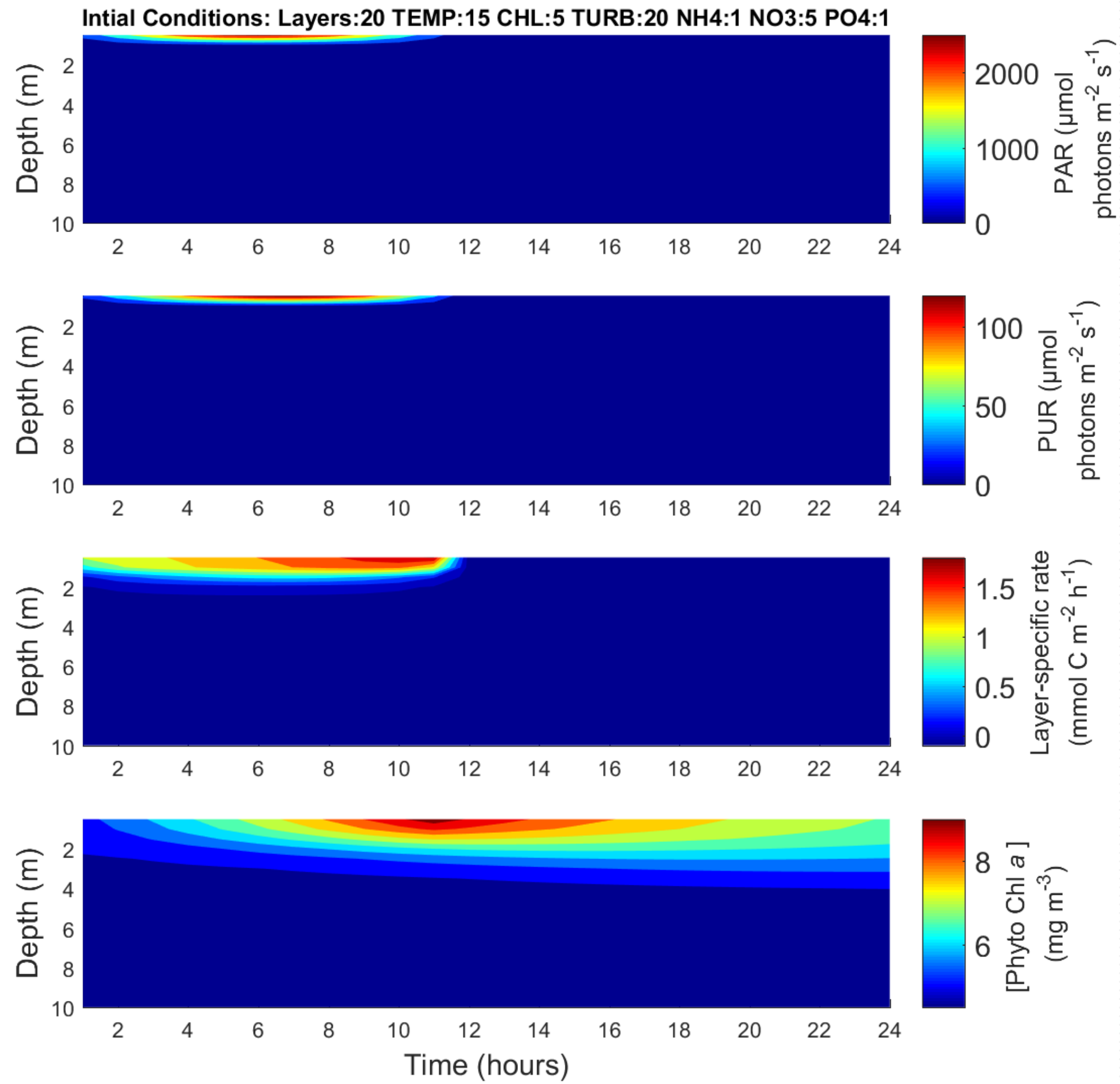

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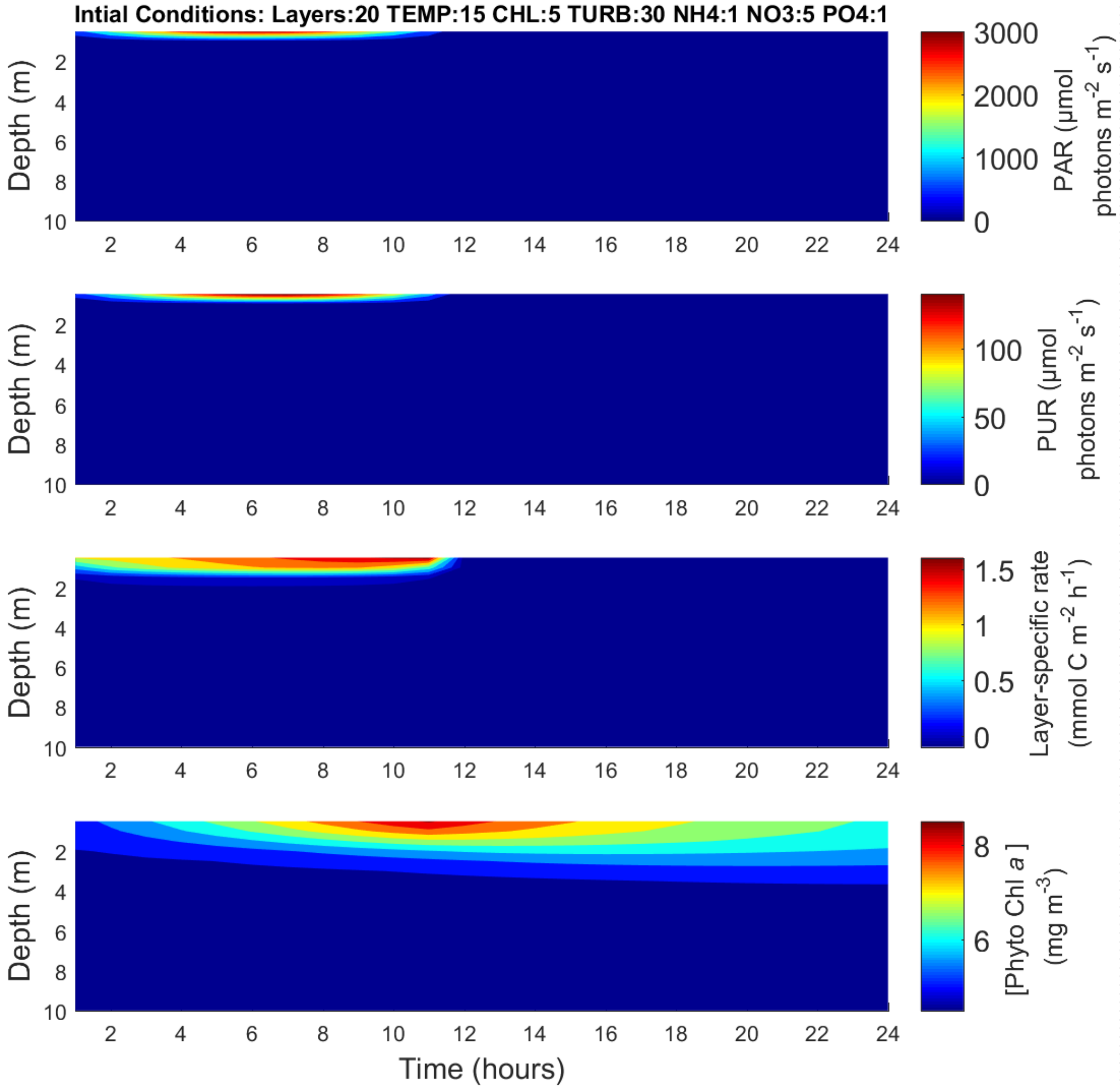

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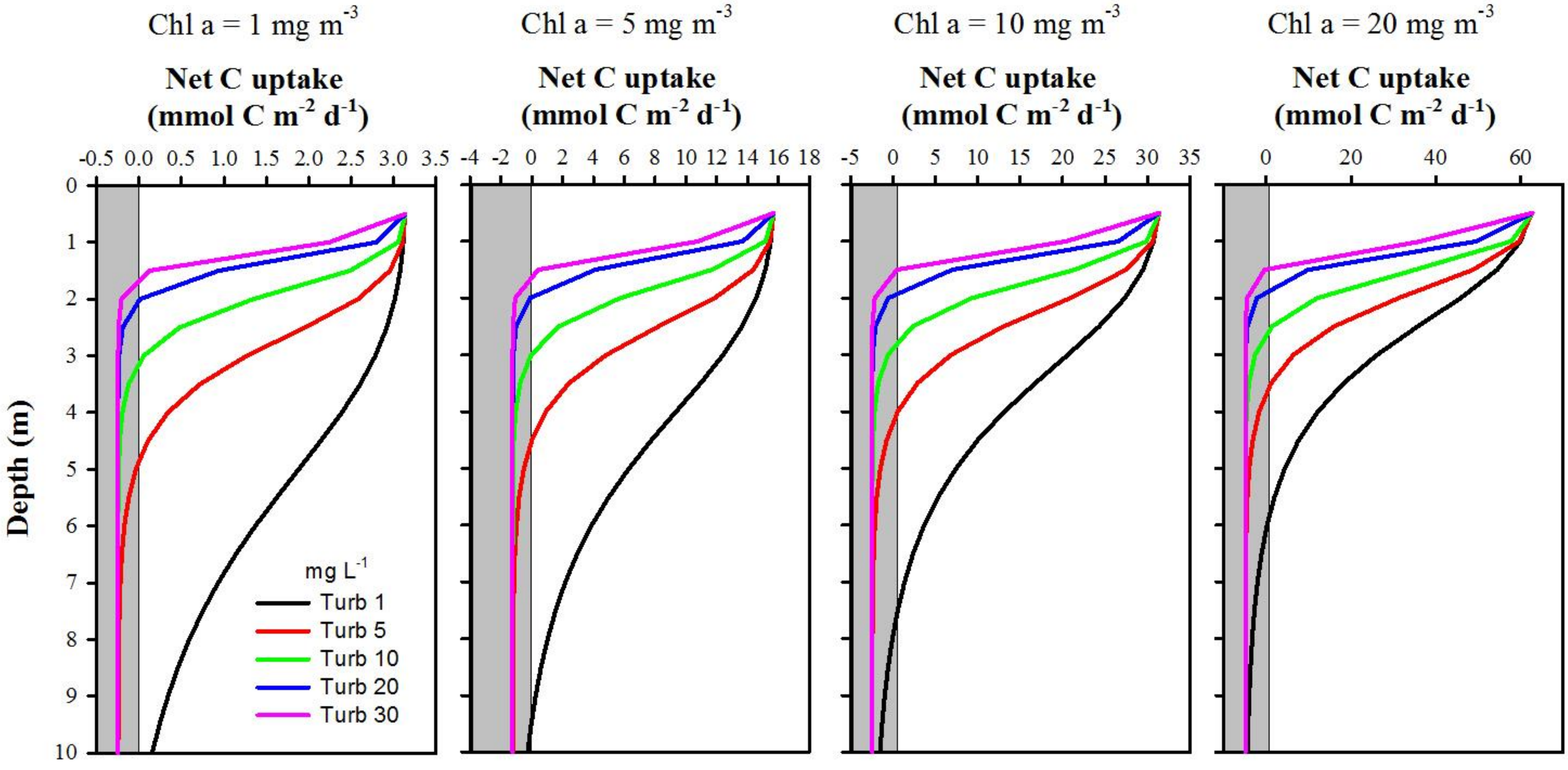

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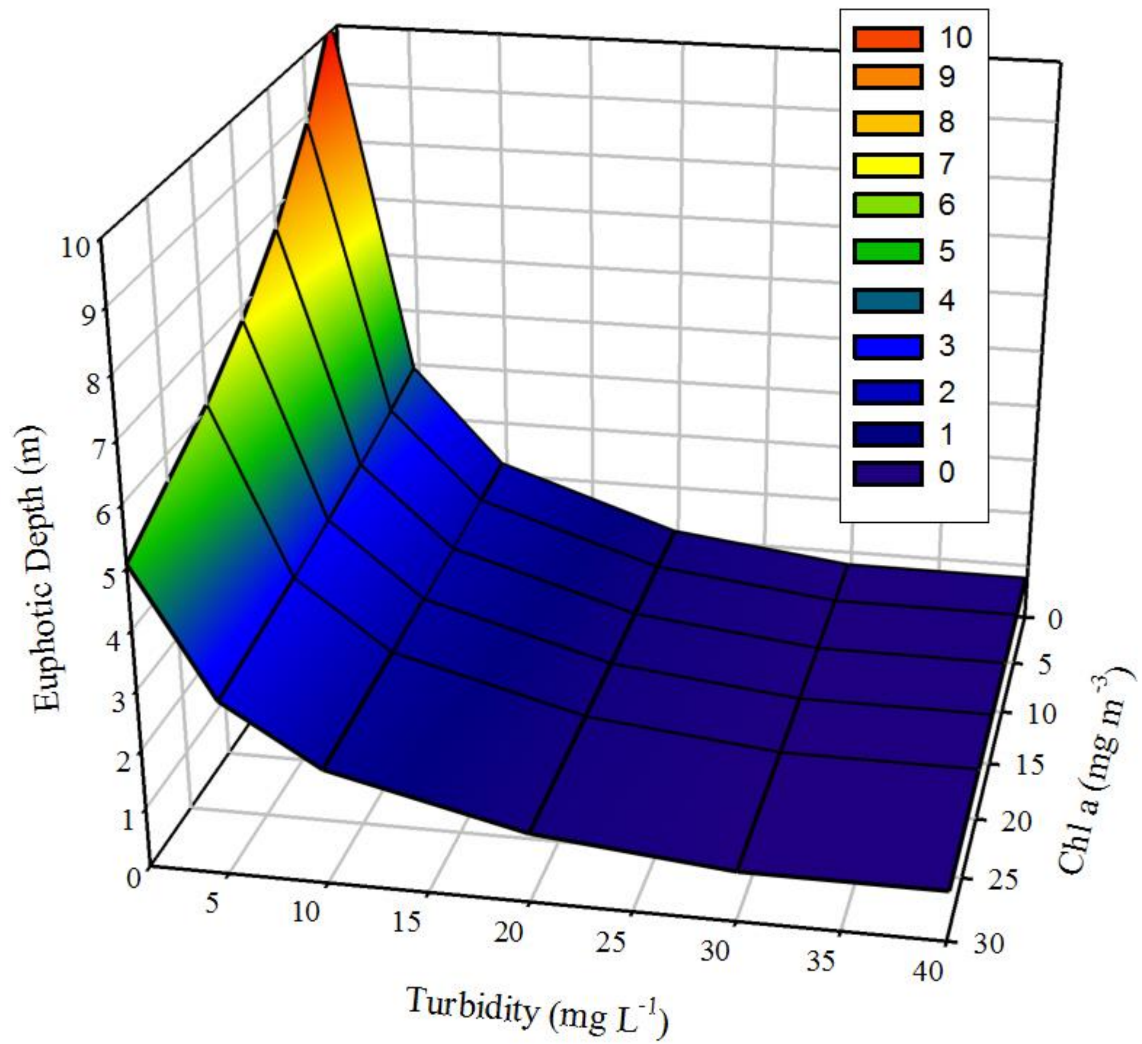
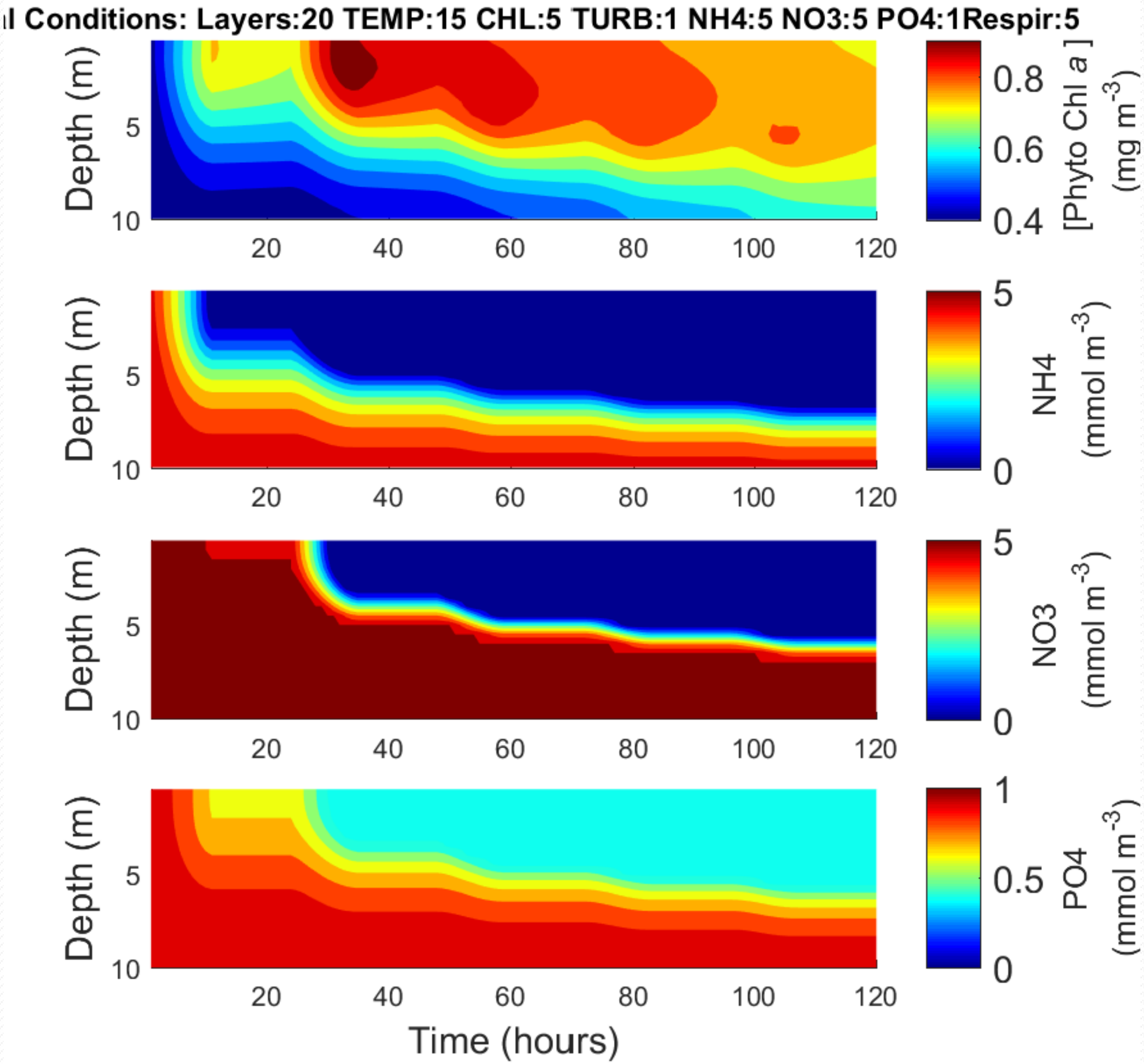


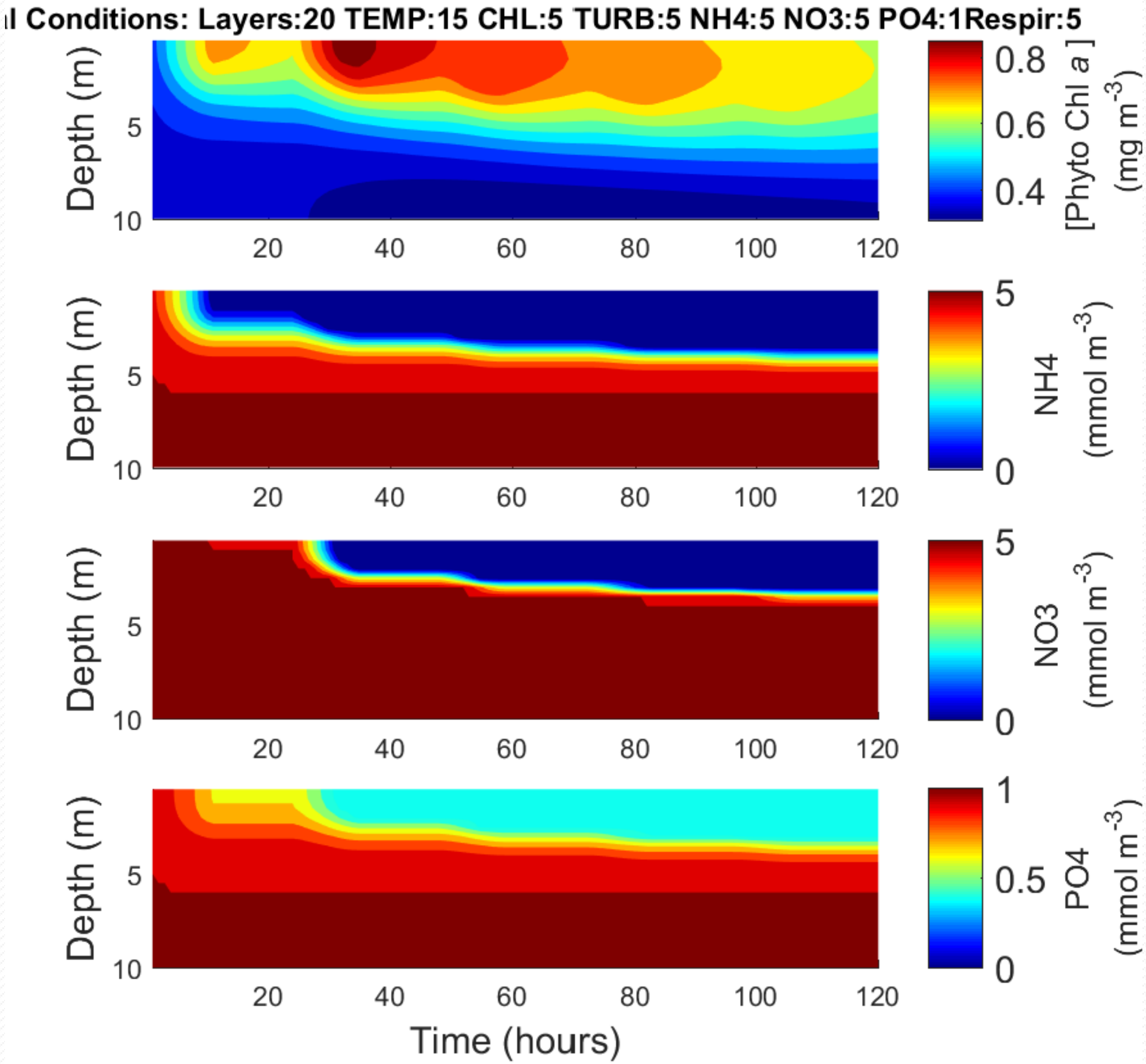
Case 2: Effect of water transparency on nutrient use

- Chl a will remain constant, TSM will increase.
- Impact NH_4, NO_3, PO_4

Effect of water transparency on nutrient use



Effect of water transparency on nutrient use



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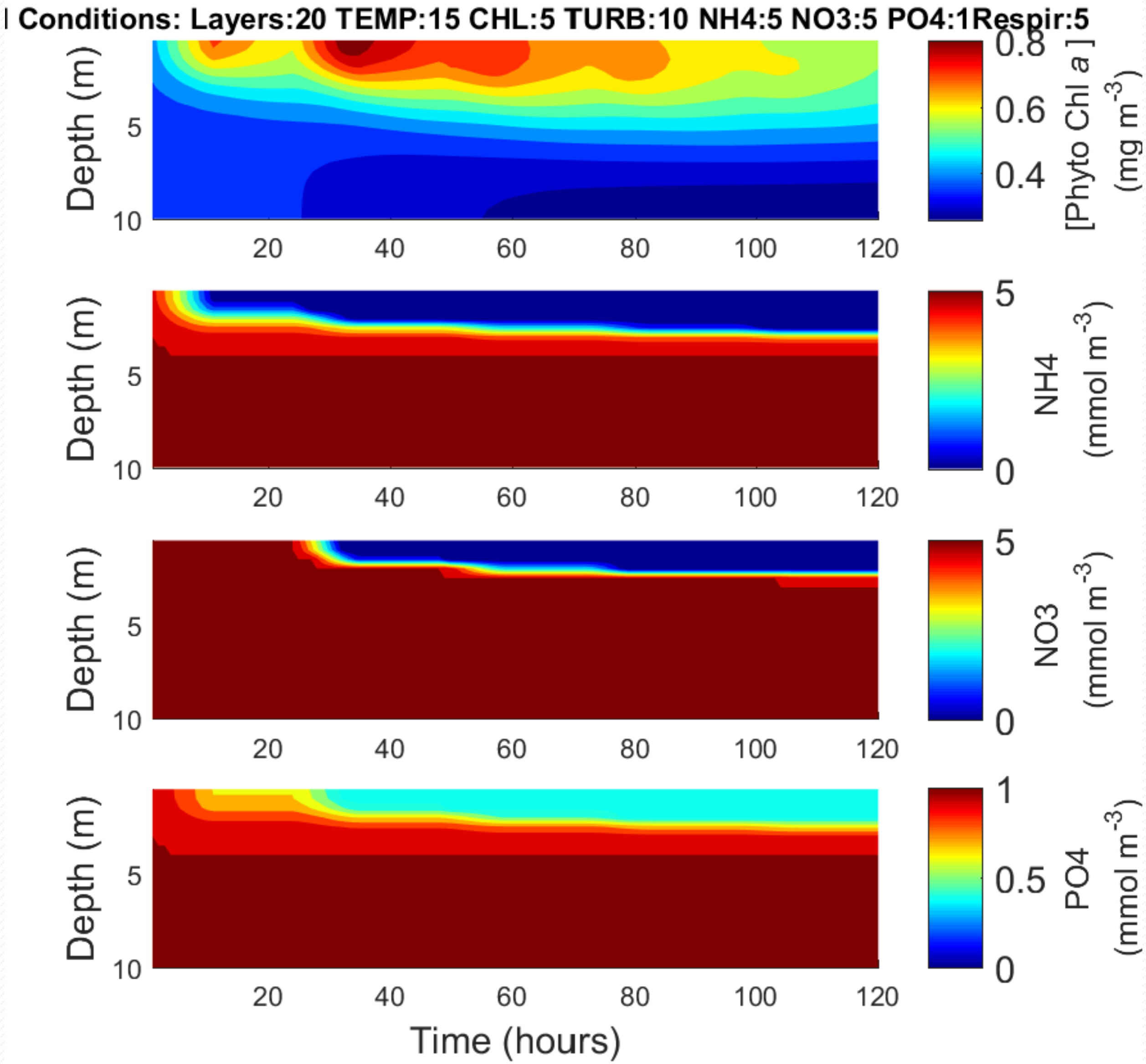

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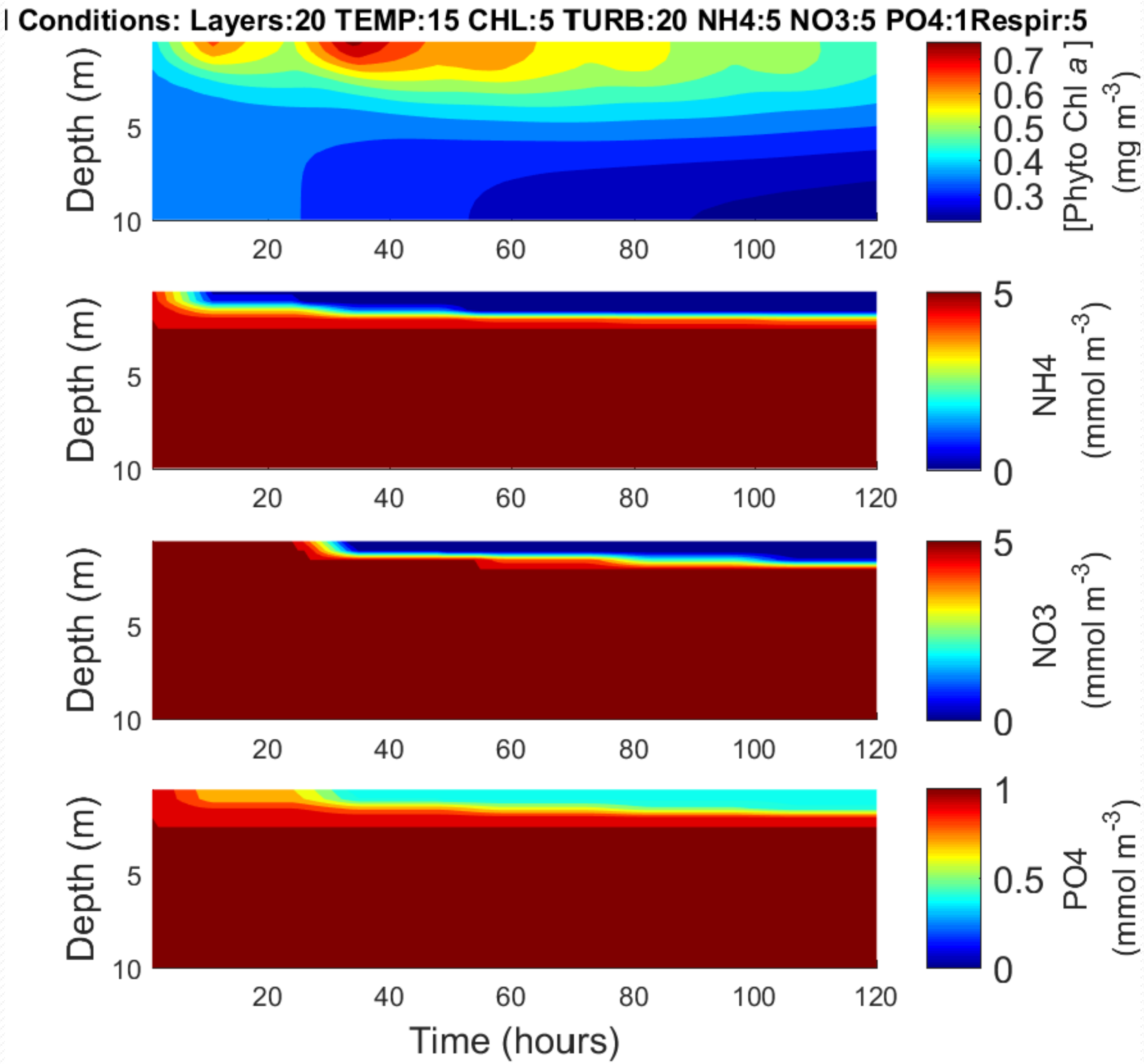
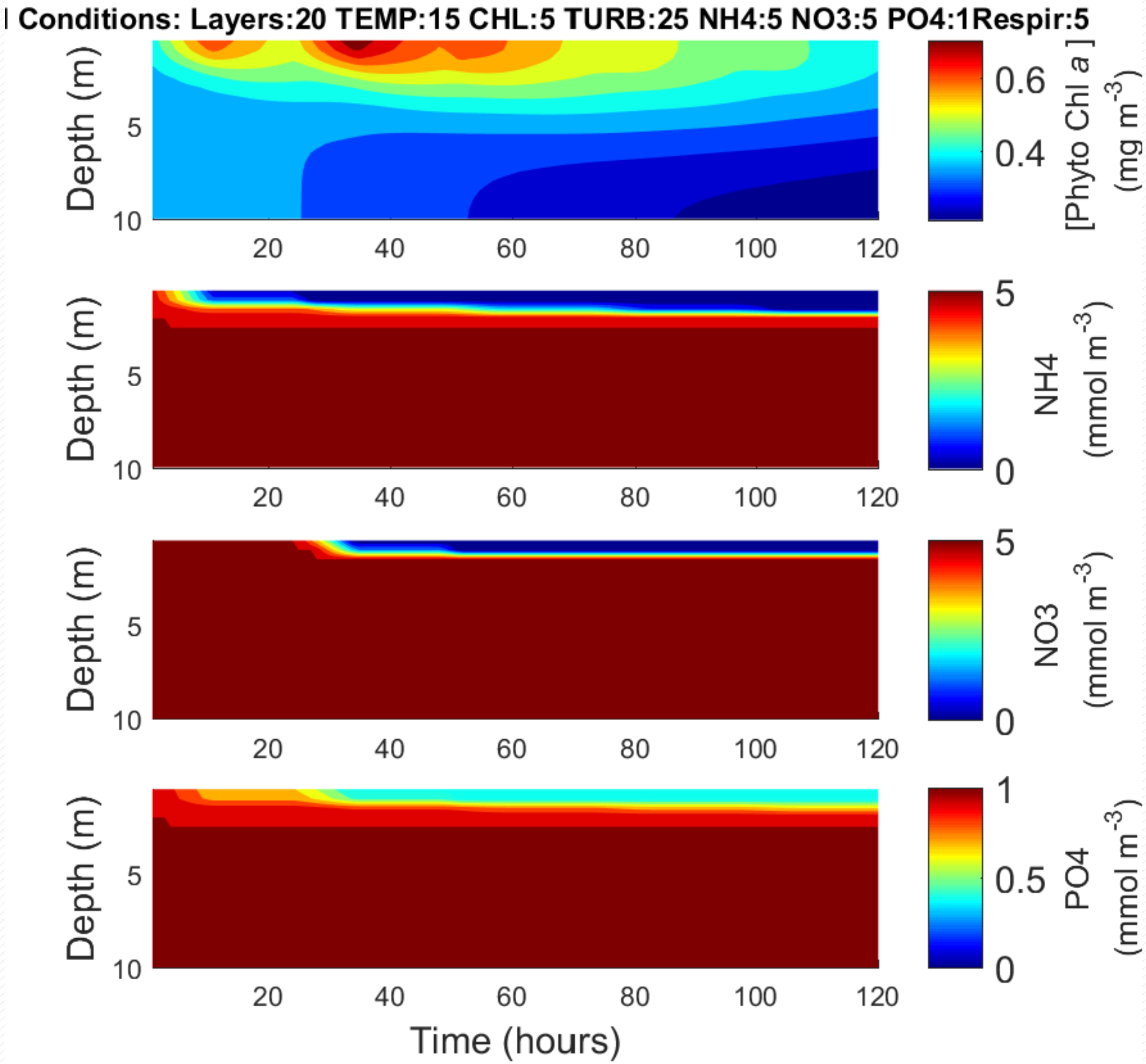
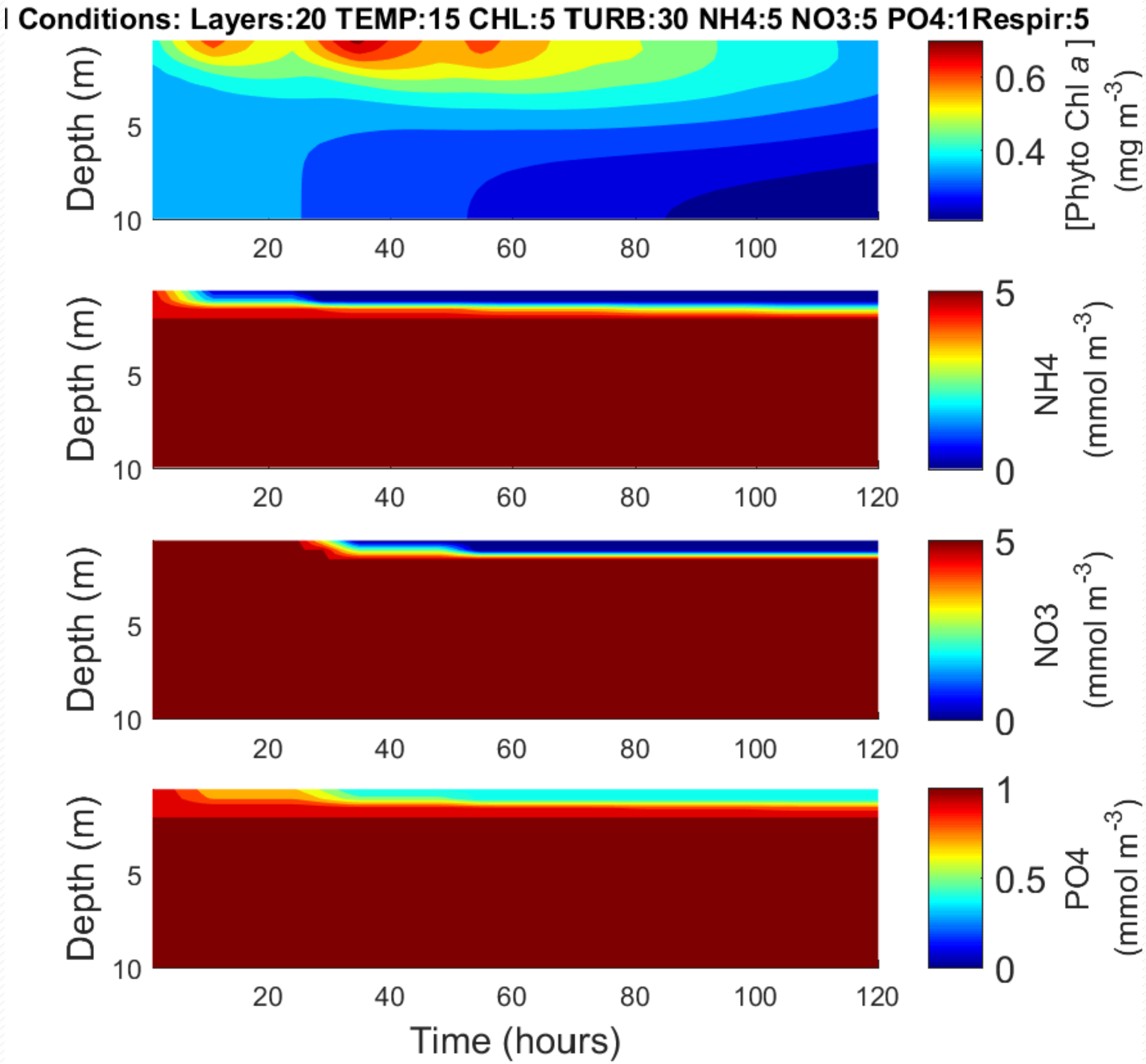


Effect of water transparency on nutrient use



Effect of water transparency on nutrient use

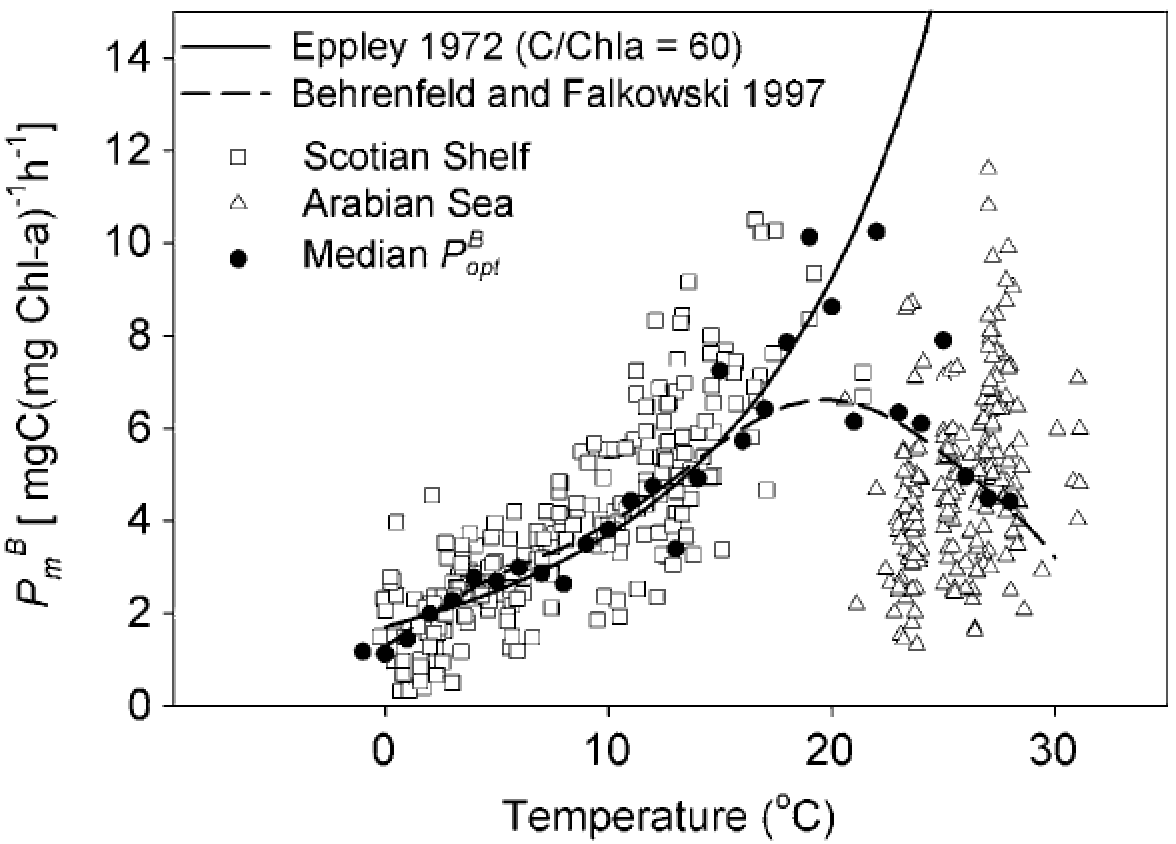


Case 3: Effect of temperature on phytoplankton carbon

Effect of temperature on phytoplankton carbon

- $P^B{}_m$ peaks at 20° C, then declines
- R increases with temp
- P:R decreases as temp increases above 20° C

- Winter = 10 °C
- Spring = 20 °C
- Summer = 30 °C

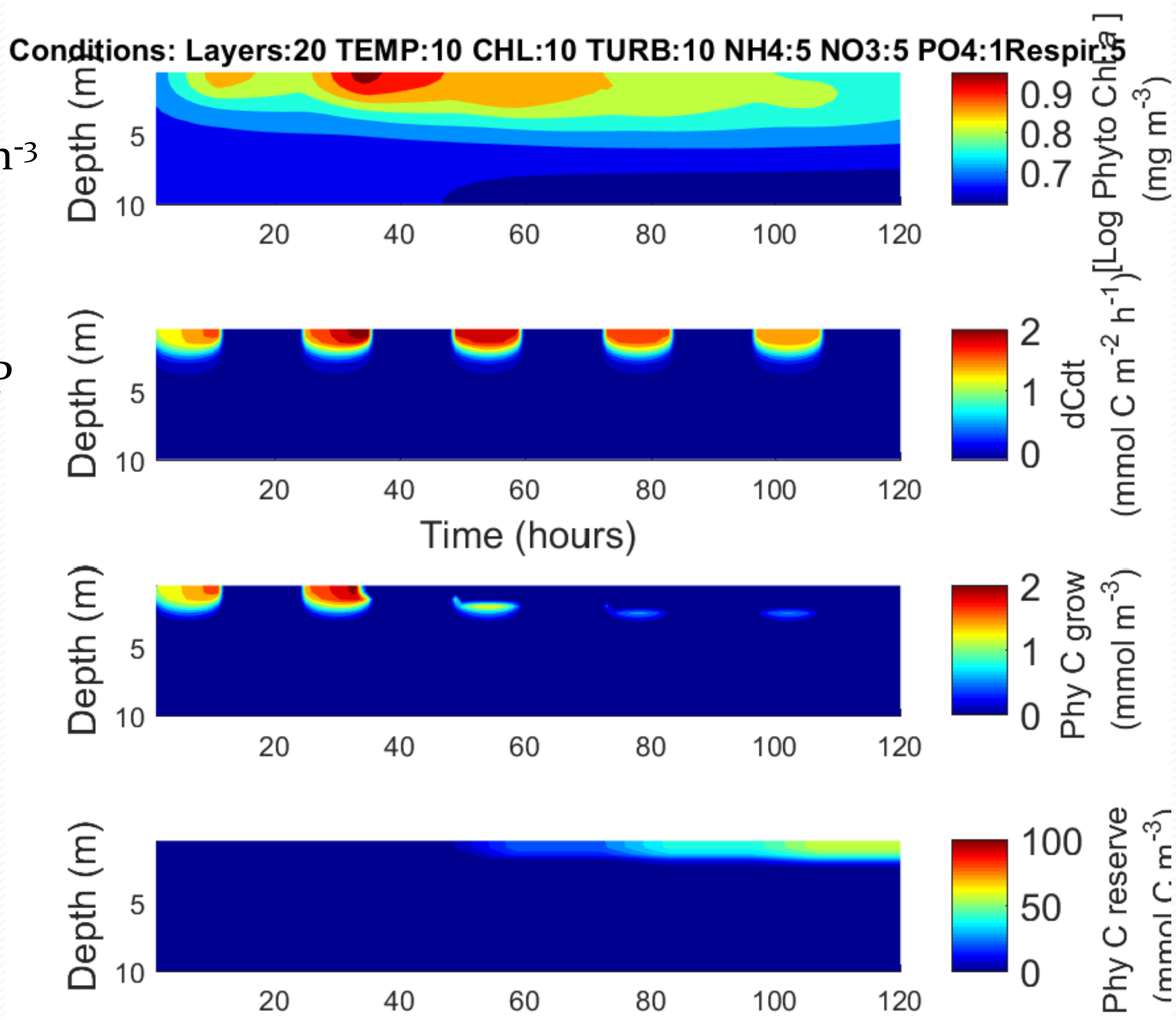


Effect of temperature on phytoplankton carbon

10 ° C
CHL = 10 mg m^{-3}
TSM 10 mg L^{-1}

Positive daily P

Growth is nut limited



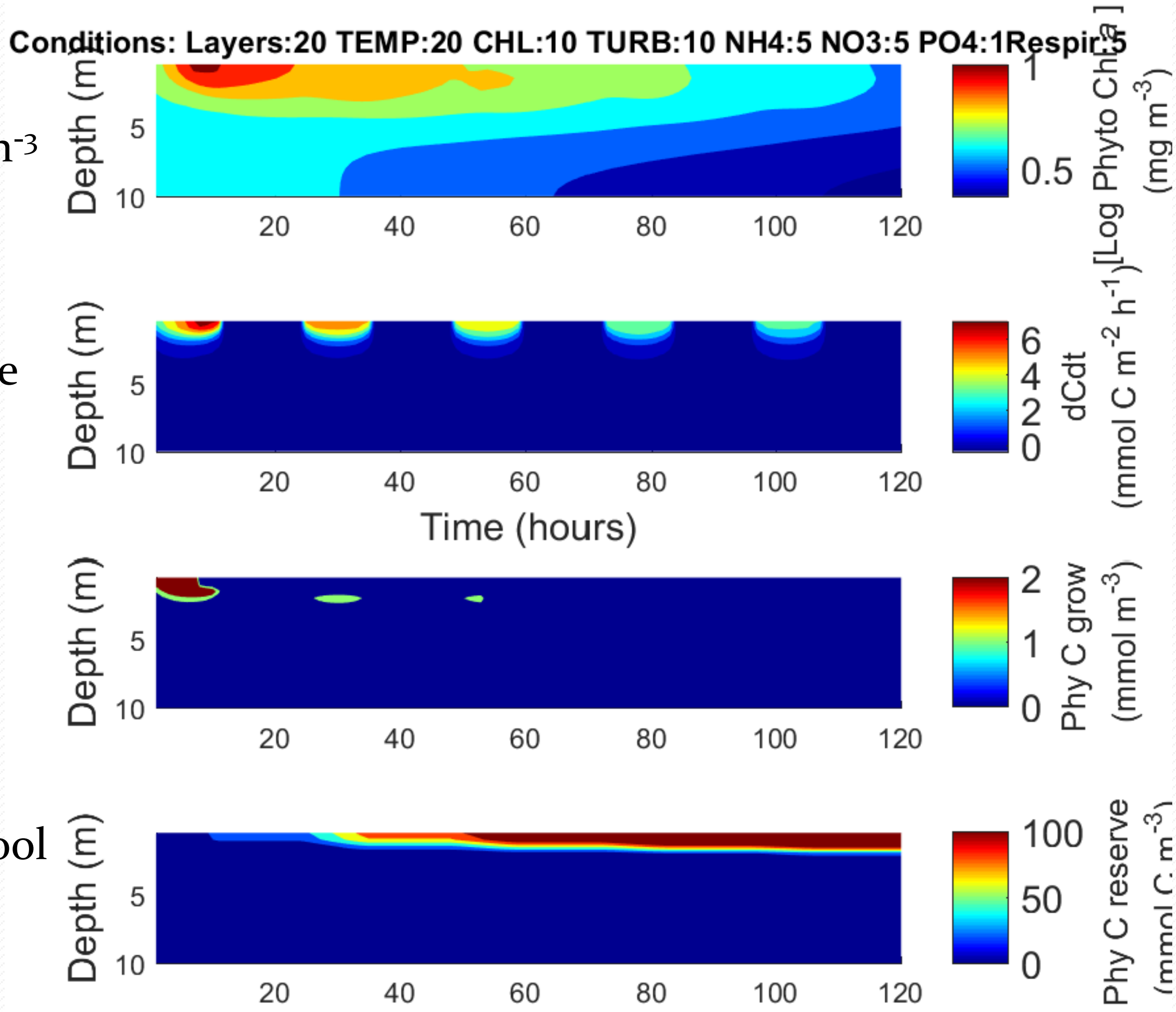
Effect of temperature on phytoplankton carbon

20 ° C
CHL = 10 mg m^{-3}
TSM 10 mg L^{-1}

Higher positive daily P

Growth is nut limited

Dissolved C pool grows

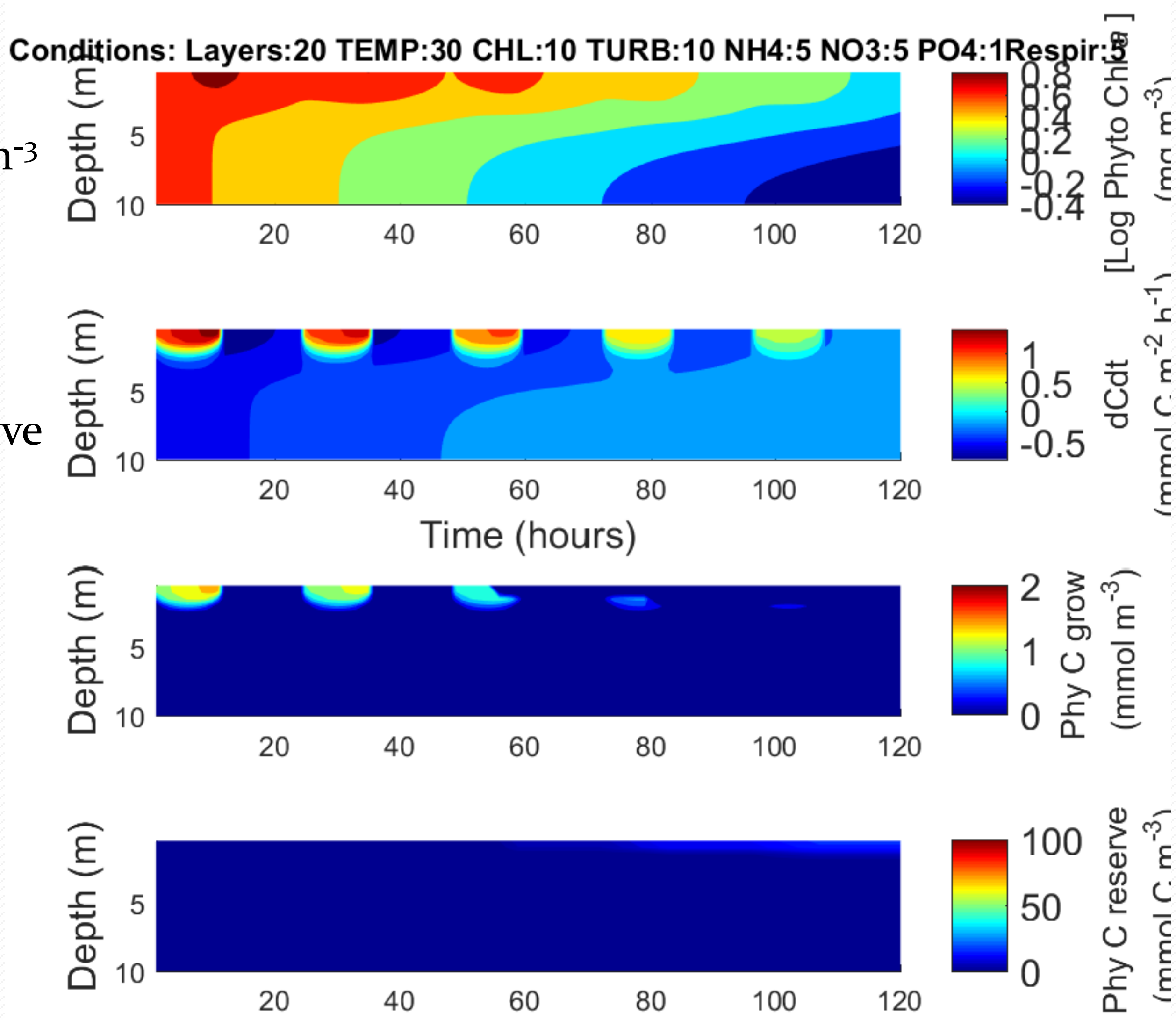


Effect of temperature on phytoplankton carbon

30 ° C
CHL = 10 mg m^{-3}
TSM 10 mg L^{-1}

Positive daily P becomes negative

Growth low



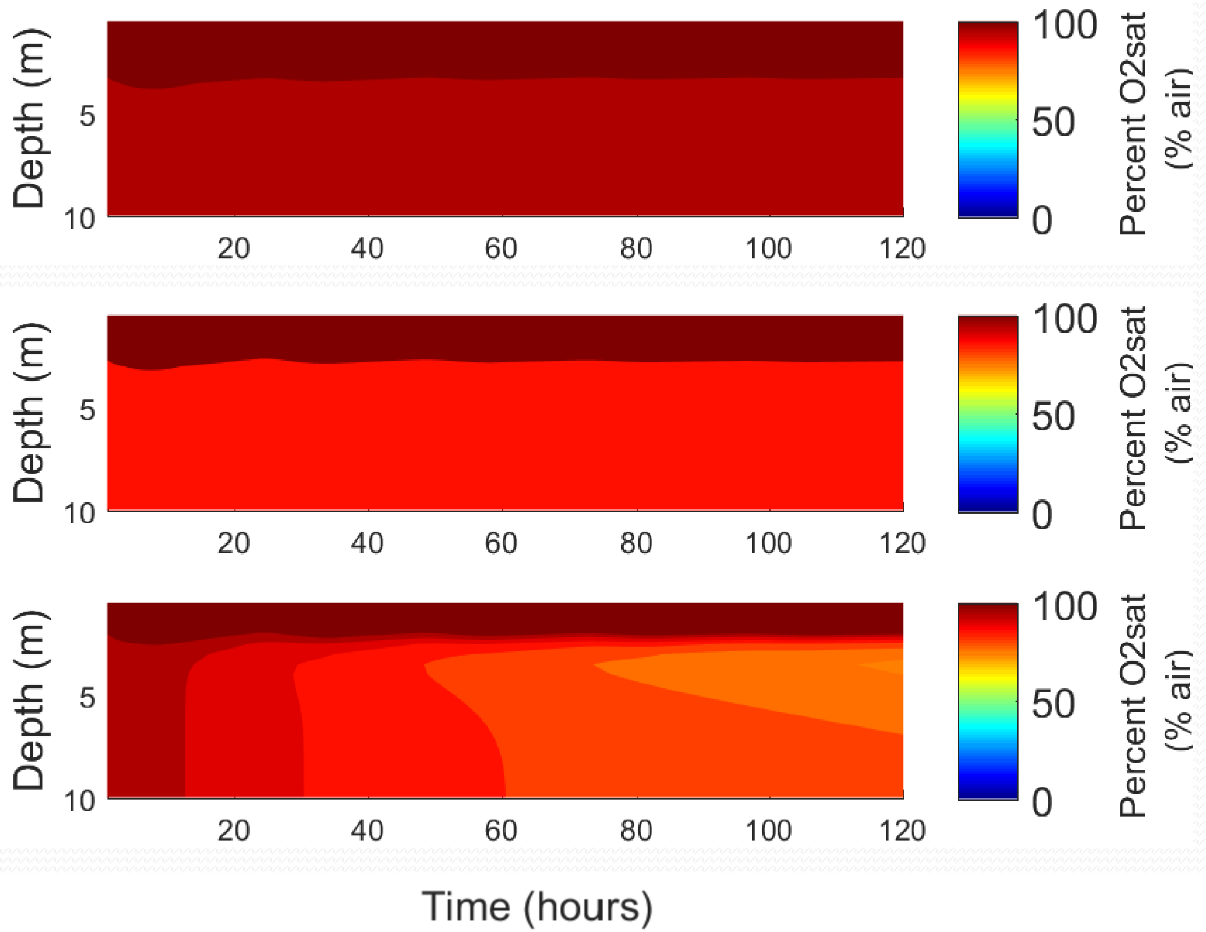
Effect of temperature on O2

CHL = 10 mg m^{-3}, TSM = 10 mg m^{-3}

10 ° C

20 ° C

30 ° C

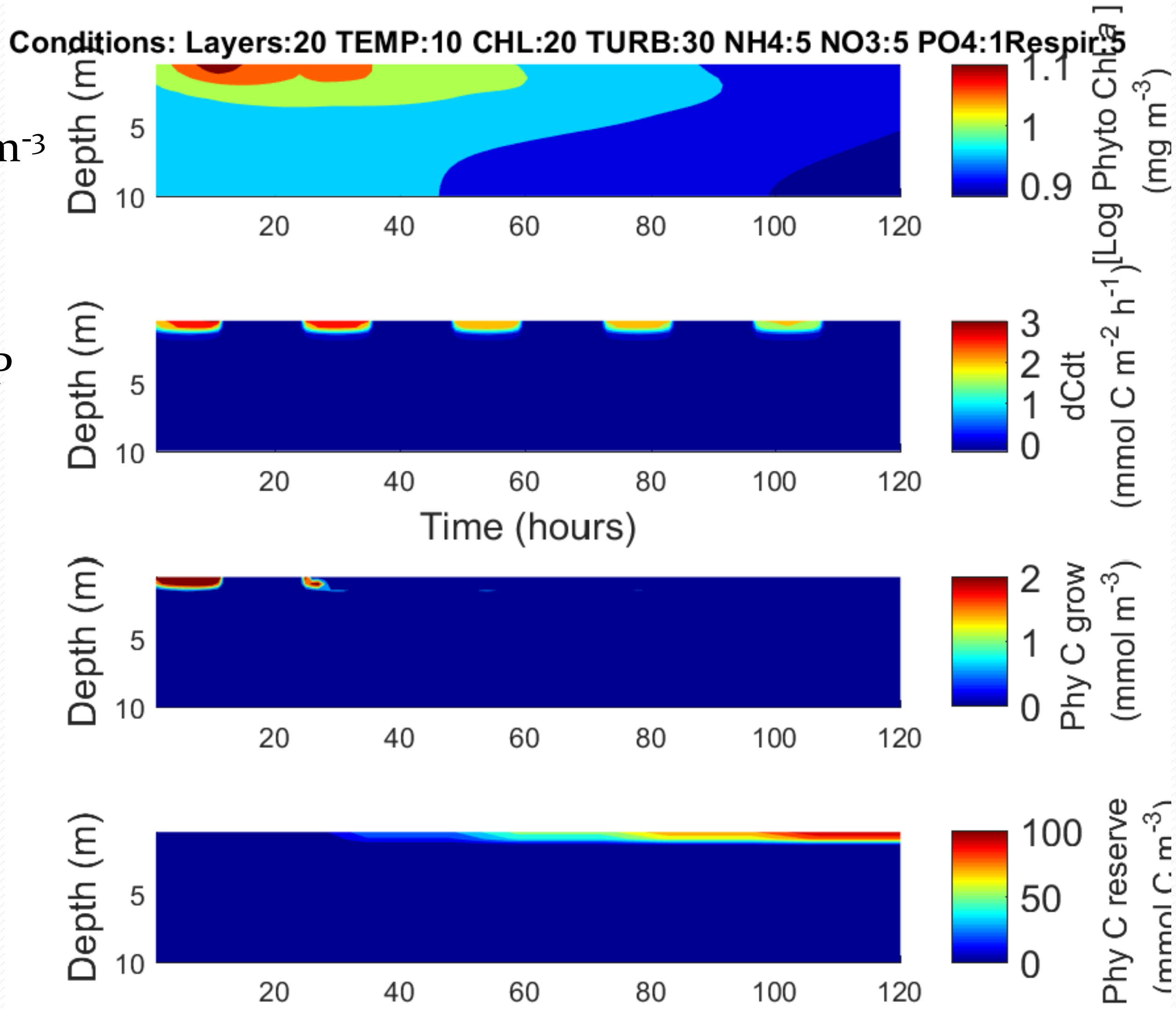


Effect of temperature on phytoplankton carbon

10 ° C
CHL = 20 mg m^{-3}
TSM 30 mg L^{-1}

Positive daily P

Growth is nut limited



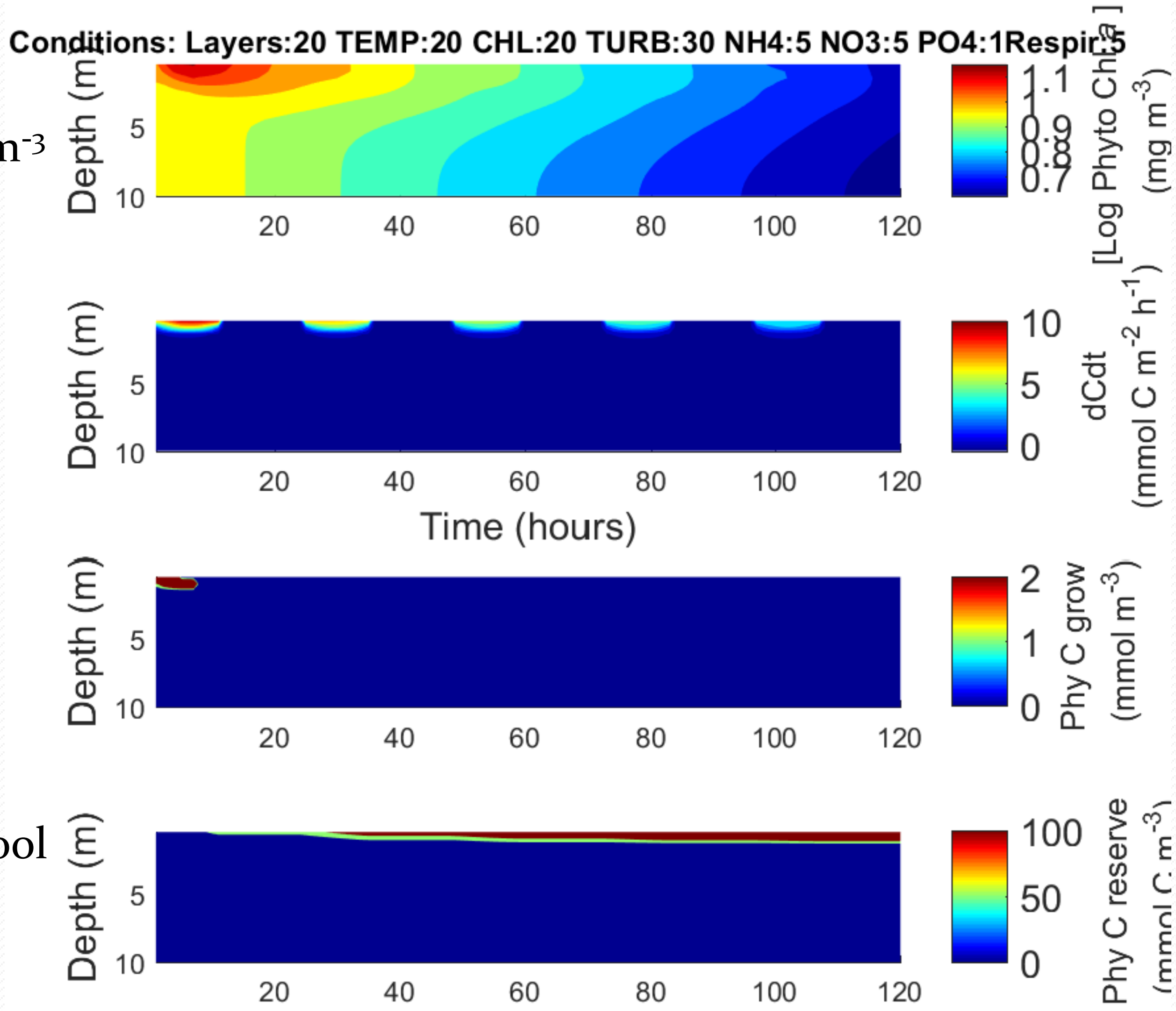
Effect of temperature on phytoplankton carbon

20 ° C
CHL = 20 mg m^{-3}
TSM 30 mg L^{-1}

Higher positive daily P

Growth is nut limited

Dissolved C pool grows

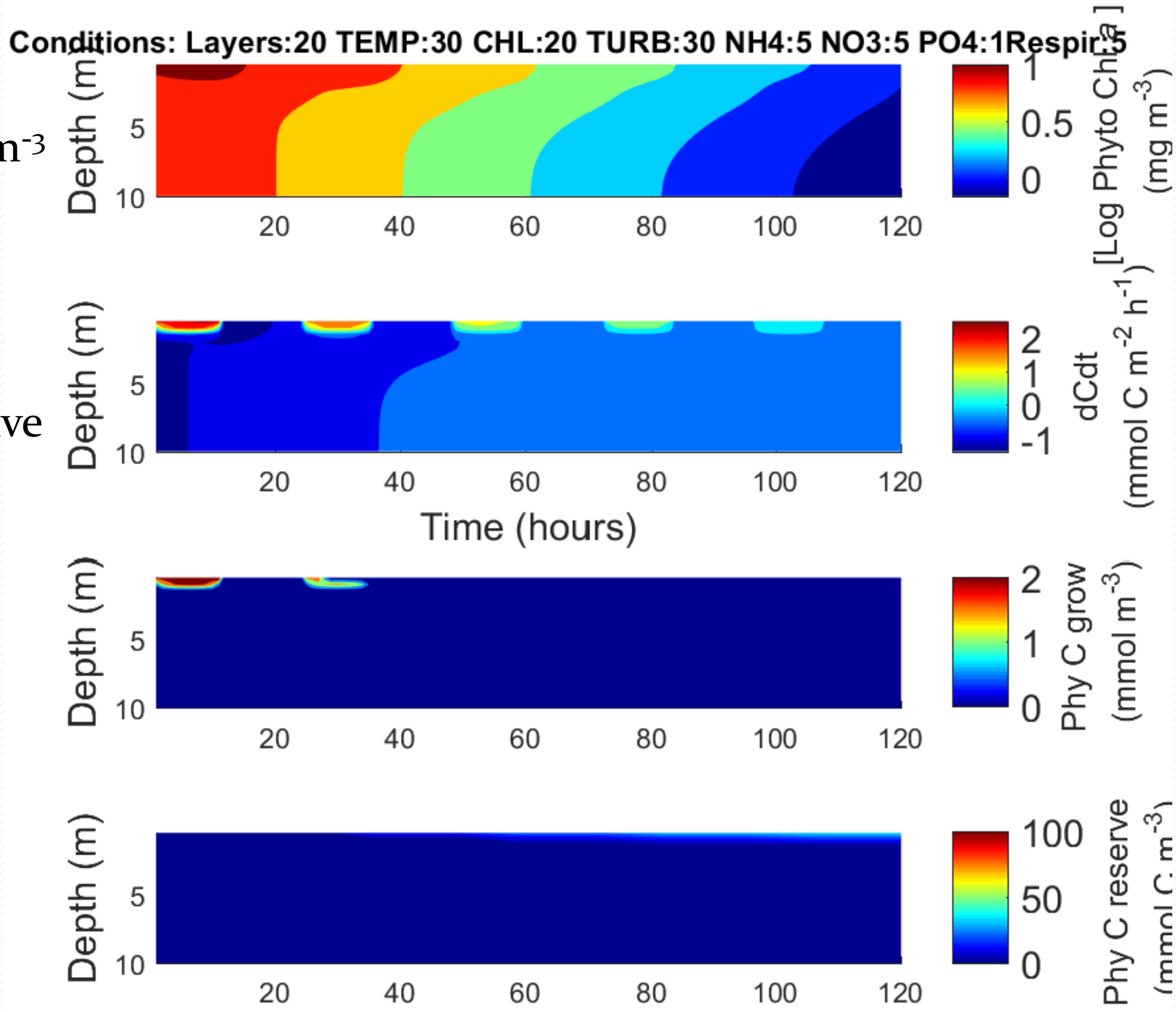


Effect of temperature on phytoplankton carbon

30 ° C
CHL = 20 mg m^{-3}
TSM 30 mg L^{-1}

Positive daily P becomes negative

Growth low



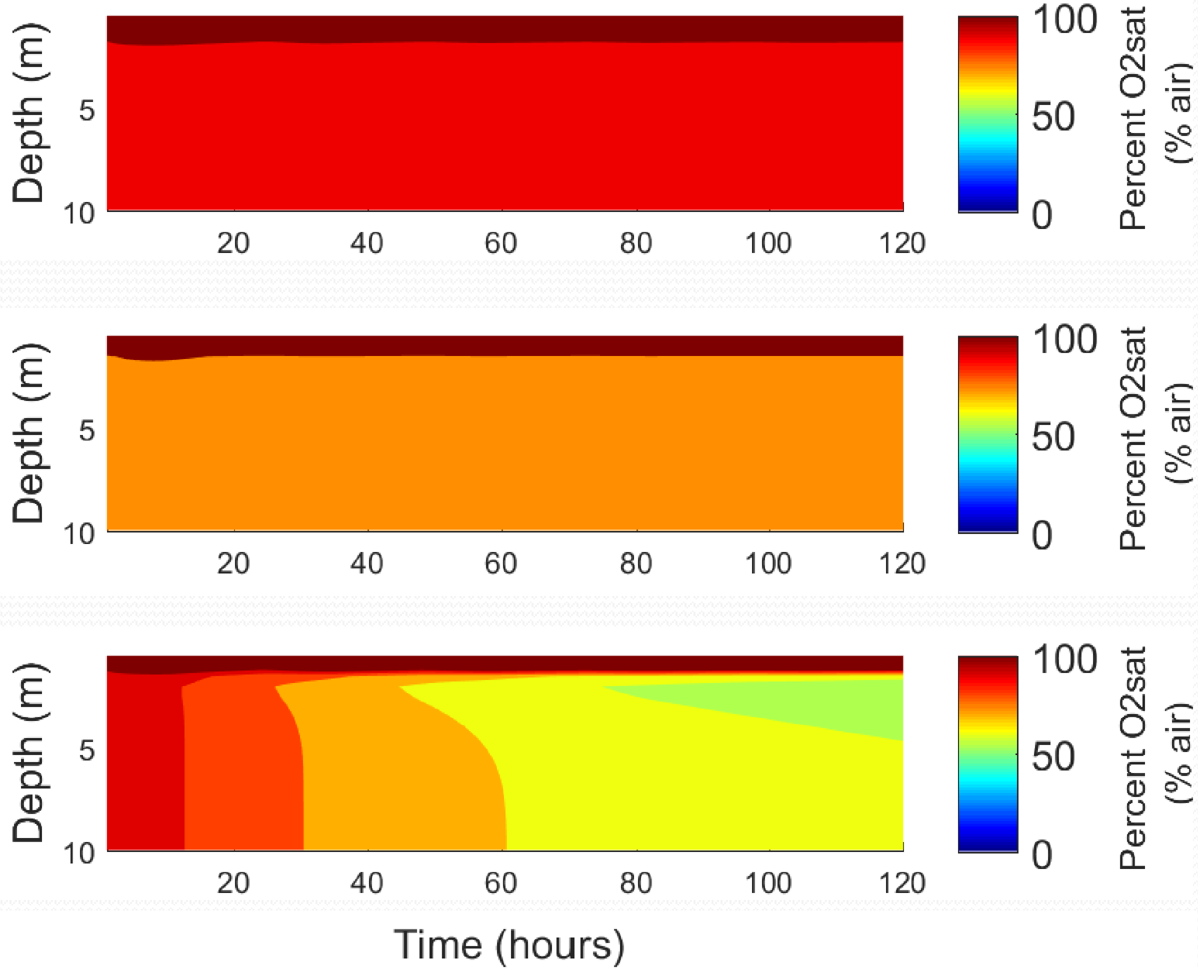
Effect of temperature on O2

CHL = 20 mg m^{-3}, TSM = 30 mg m^{-3}

10 ° C

20 ° C

30 ° C



Case 4: Effect of heterotrophic respiration on phytoplankton carbon

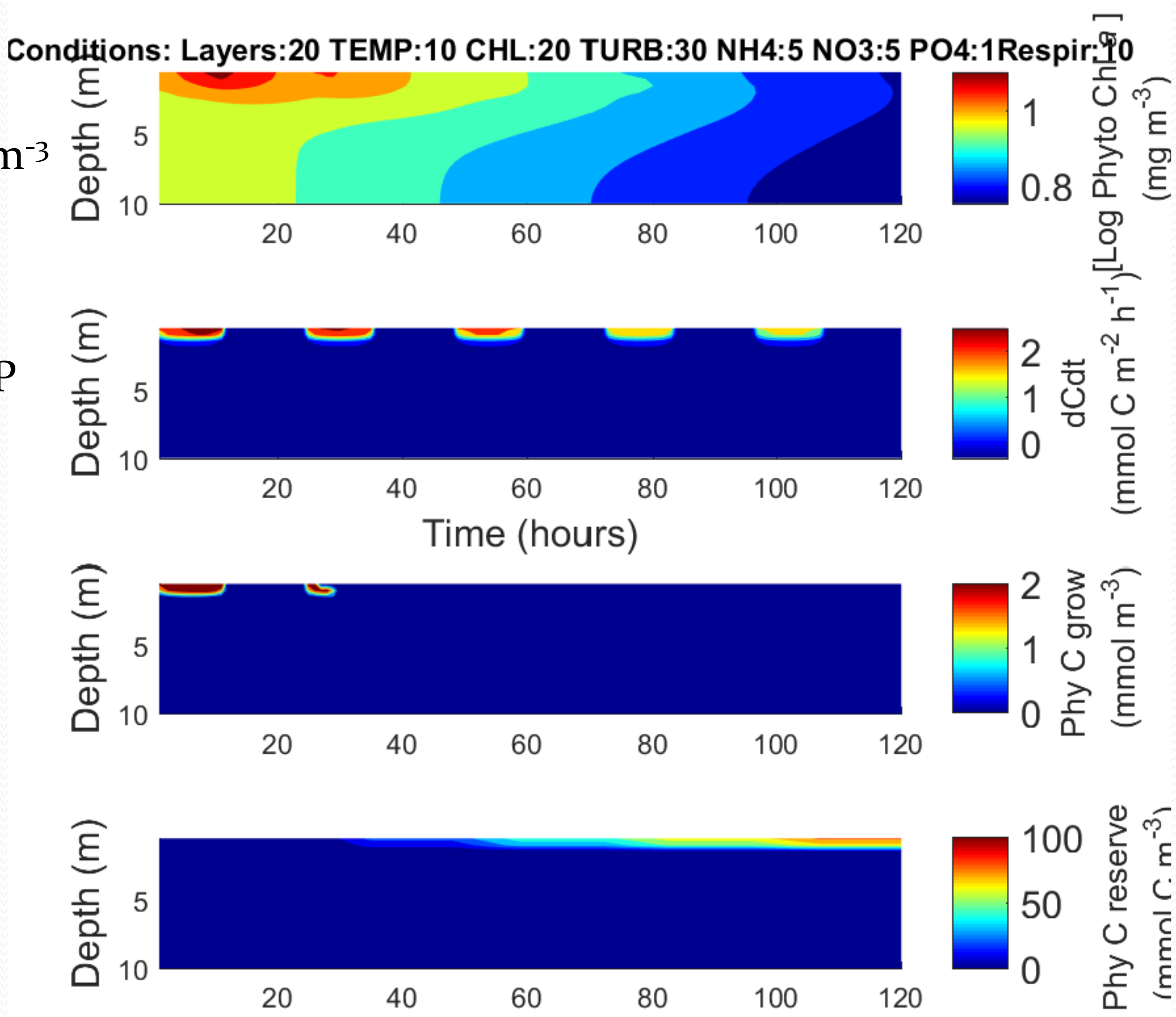
- Increase respiration to 10% of Pmax

Effect of heterotrophic respiration on phytoplankton carbon

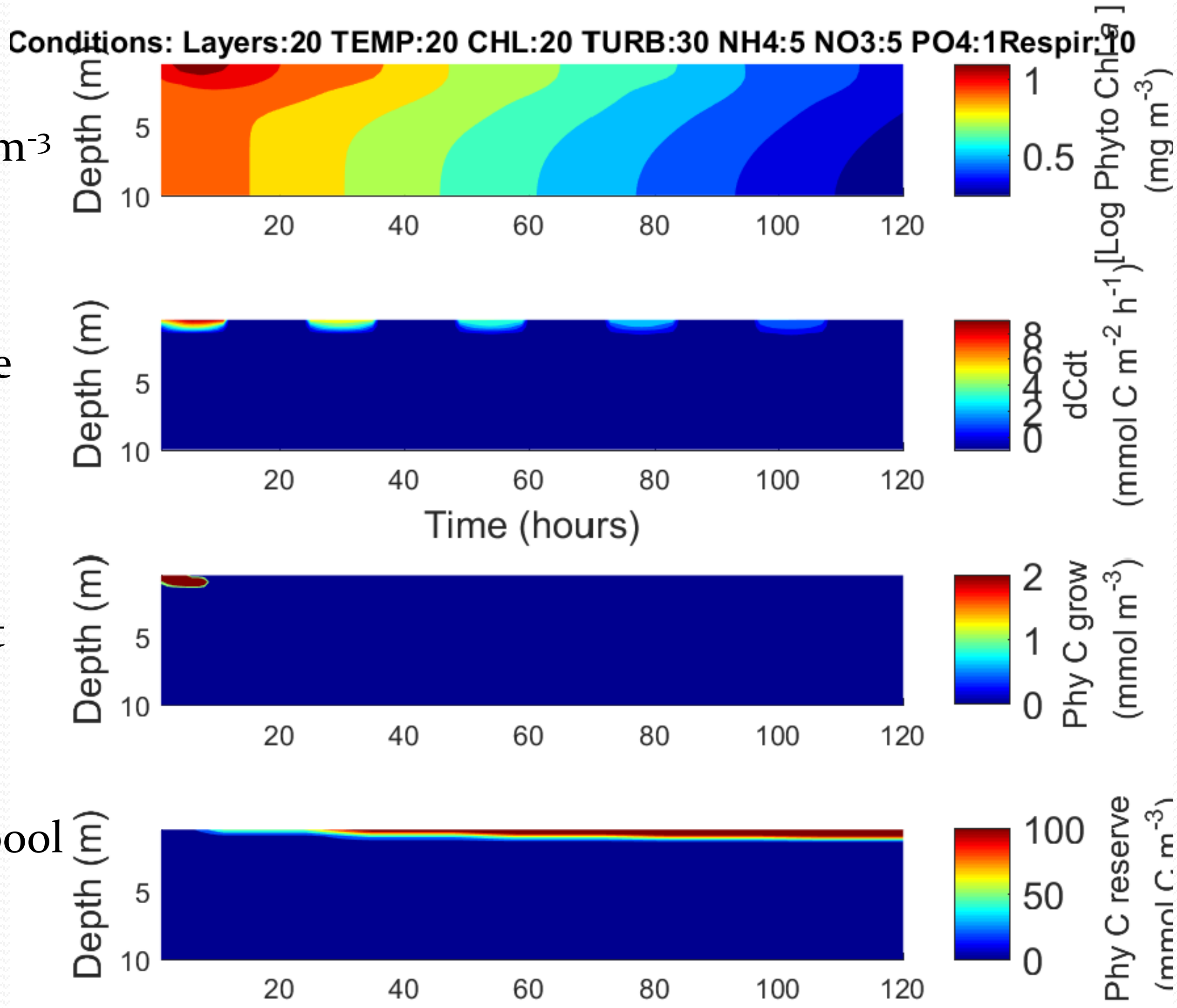
10 ° C
CHL = 20 mg m^{-3}
TSM 30 mg L^{-1}

Positive daily P

Growth is nut limited



Effect of heterotrophic respiration on phytoplankton carbon



20 ° C
CHL = 20 mg m^{-3}
TSM 30 mg L^{-1}

Higher positive daily P

Growth is nut limited

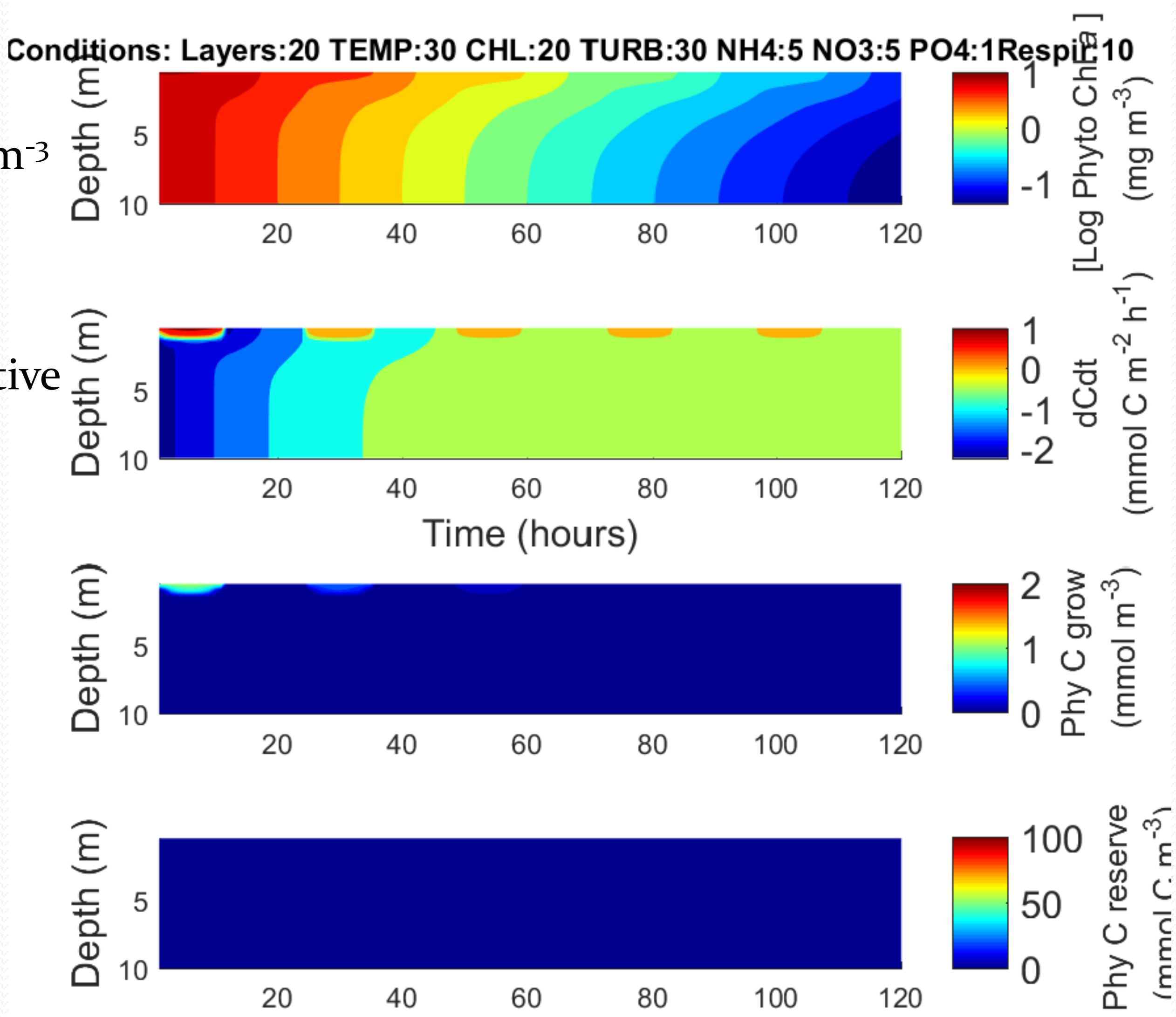
Dissolved C pool grows

Effect of heterotrophic respiration on phytoplankton carbon

30 ° C
CHL = 20 mg m^{-3}
TSM 30 mg L^{-1}

P is barely positive

Growth low



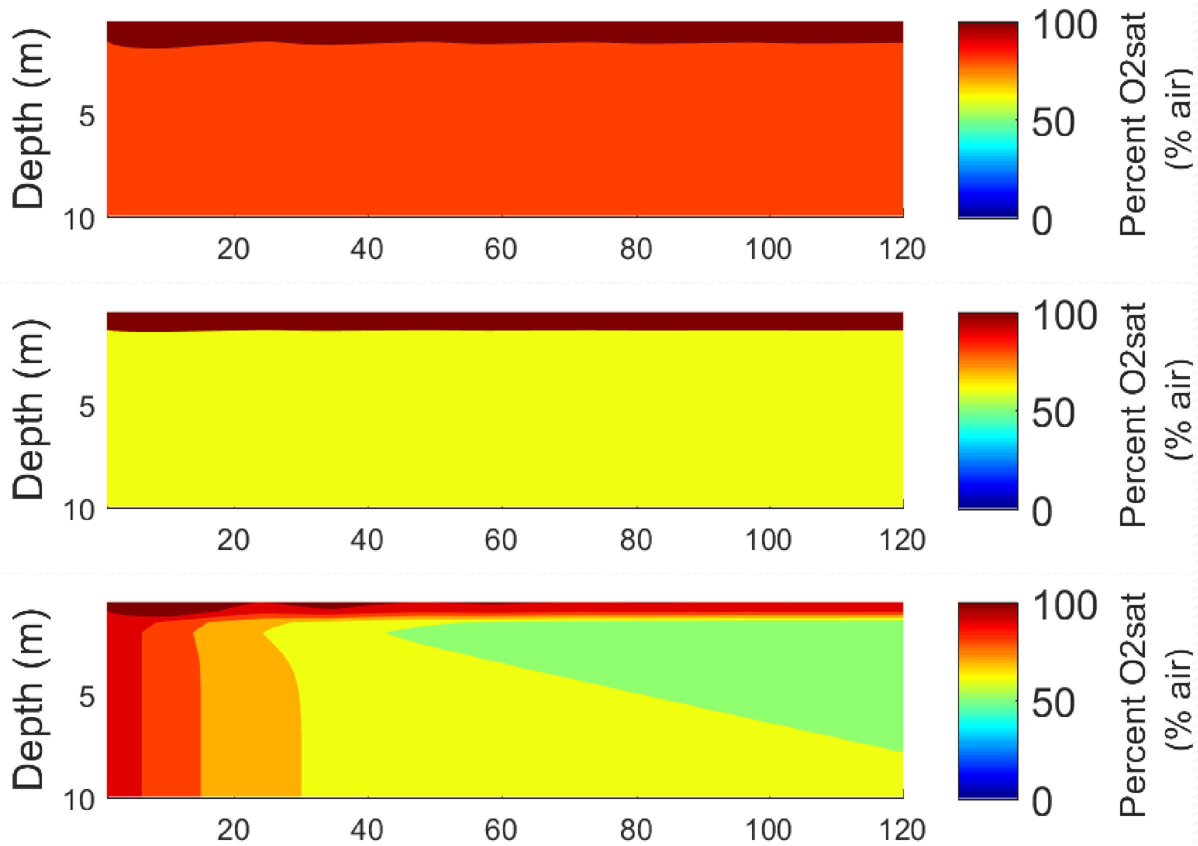
Effect of heterotrophic respiration on phytoplankton carbon

CHL = 20 mg m^{-3}, TSM = 30 mg m^{-3}, Respiration = 10%

10 ° C

20 ° C

30 ° C



Conclusions

- *GrassLight* accurately predicts
  - Suggests potential for SAV expansion in response to improved water quality
- Phytoplankton module indicates
  - Chester River light limited from suspended particulates more than phytoplankton
    - Sediment and organic detritus
  - Nutrient utilization is controlled by light
  - Vulnerable to hypoxia in the summer
- Get the light right and the WQ will follow

Controls on aquatic photosynthesis

- Salinity
- Light
- Nutrients
- Temperature
- CO_2
- Grazing
- Sinking