Impact of biological feedback on heat fluxes and sea surface temperature in global and regional ocean models

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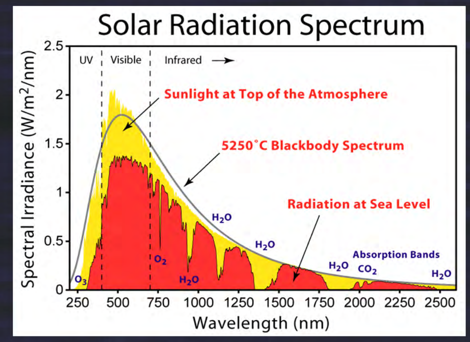
Abstract

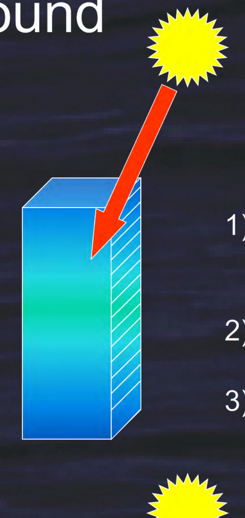
Ocean models require parameterization of the penetrative length scales of shortwave irradiance into the surface ocean. Surface ocean biology may modulate this length scale on a variety of space-time scales and this variability may, in turn, impact numerical model forecasts of surface ocean temperatures and ocean-atmosphere heat exchange. We present results from both global and regional ocean forecasting systems evaluating the sensitivity of the systems to various representations of surface ocean bio-optical variability. Global numerical experiments with the Hybrid Coordinate Ocean Model (HYCOM) demonstrate secondary circulation effects due to bio-optical variability in surface waters. Regional-scale two-way coupled ocean atmosphere systems further indicate a significant impact on turbulent thermal energy exchanges when coastal phytoplankton blooms are represented in the modeling system.

Background



The depth penetration of solar energy into the ocean is largely determined by spectral absorption coefficients:

$$a_t(\lambda) = \underbrace{a_\varphi(\lambda) + a_{cdm}(\lambda)}_{f\text{ (biological processes)}} + a_{sw}(\lambda)$$

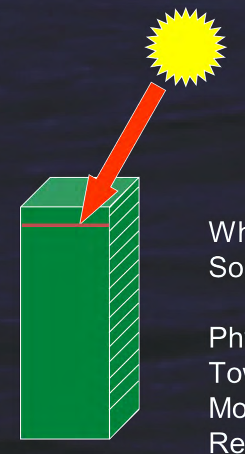


How should we represent absorption of solar energy in the ocean models?

1) A Constant Value (Jerlov Water Types)
   *A Common Default [Paulson and Simpson 1977]

2) 2-D Fields from Satellite Ocean Color Data

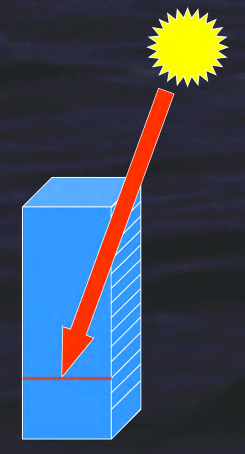
3) 4-D space-time variability from an interactive ocean bio-optical model



$$a_t(\lambda) = \underbrace{a_\varphi(\lambda) + a_{cdm}(\lambda)} + a_{sw}(\lambda)$$

When these terms are large (eutrophic)
Solar Transmission Length Scale is small

Physical Tendencies (relative to oligotrophic):
Towards higher Sea Surface Temperature (SST)
More energy trapped near surface
Reduced mixed layer depth (MLD)

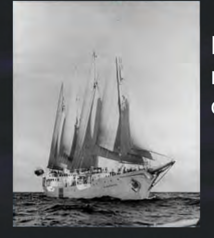


$$a_t(\lambda) = \underbrace{a_\varphi(\lambda) + a_{cdm}(\lambda)} + a_{sw}(\lambda)$$

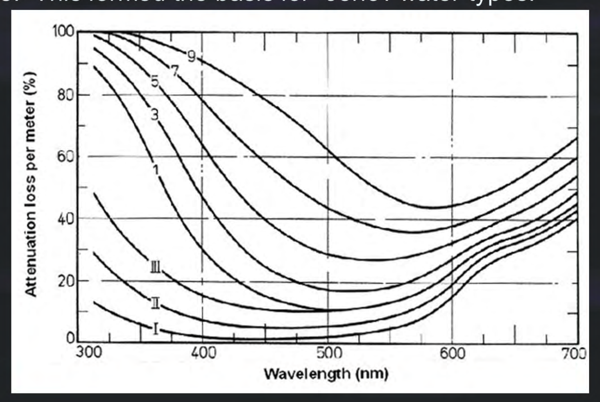
When these terms are small (oligotrophic)
Solar Transmission Length Scale is large

Physical Tendencies (relative to eutrophic):
Towards lower SST
Less energy trapped near surface
Increased MLD

Problem: Some operational models use constant "Jerlov Water Types" to represent Solar Transmission Length Scales (STS).



Nils Gunnar Jerlov performed numerous Secchi disc depth measurements on the Swedish *Albatross* Deep Sea Expedition of 1947-48. This formed the basis for "Jerlov water types."



Nominal, globally constant, Jerlov Type I STS values Ignore dynamic bio-optical variability.

Importance of ocean biological "heat trapping" or bio-feedback:

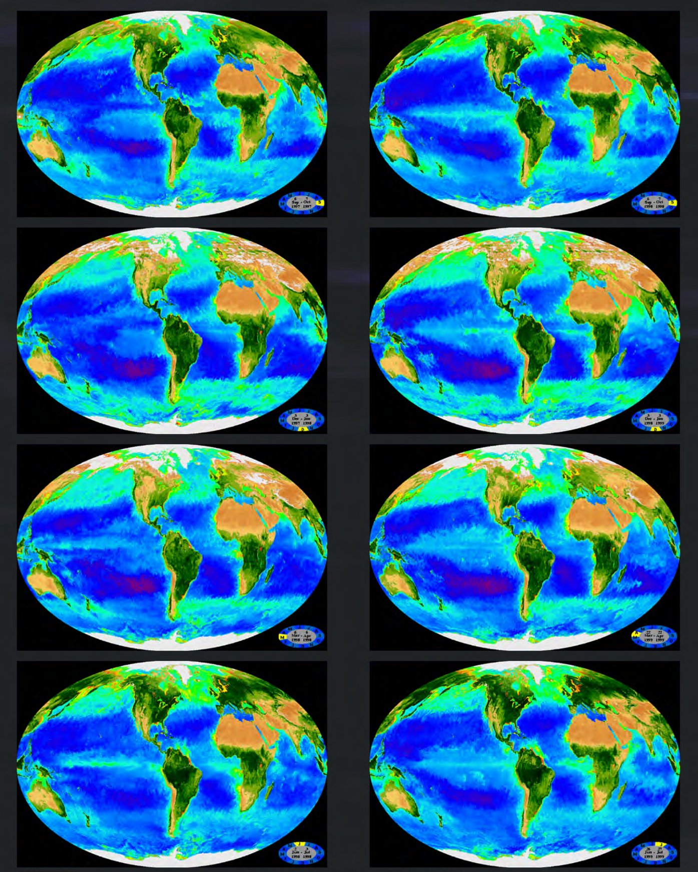
Observations: Large vertical temperature gradients (4.7°C) are seen within a coastal phytoplankton bloom [Ramp et al., 1991].

Models: Literature studies (e.g. Lengaigne et al., 2007; many others) confirm that ocean circulation model simulations are sensitive to the biological heat trapping effect:

- upper ocean temperature
- buoyancy
- mixed layer depth
- currents

Similar sensitivities are found in the ocean circulation models used for Navy forecasting. [Rochford et al., 2001; Kara et al., 2004, 2005]

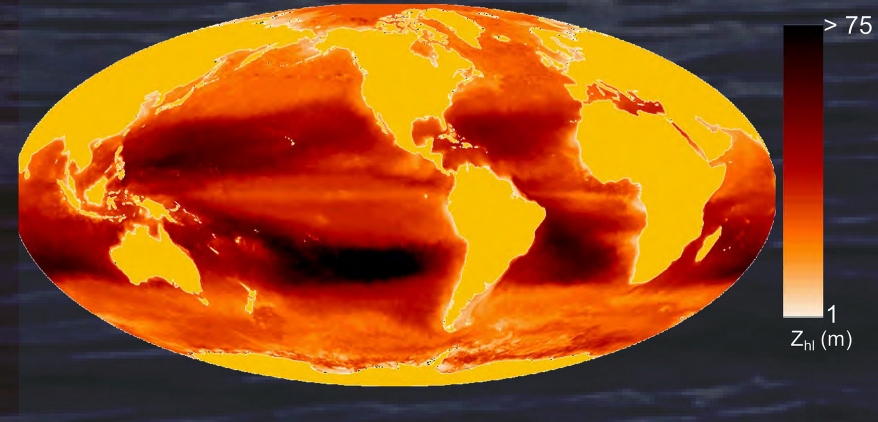
The static "Water Type" concept is obsolete. Examples from SeaWiFS 8D, 9 km composite ocean color imagery with the land vegetation index overlay show significant bio-optical variability in space and time.



Images selected from NASA GSFC oceancolor.gsfc.nasa.gov/SeaWiFS/HTML/SeaWiFS.BiosphereAnimation.70W.html

Global HYCOM Bio-Feedback

Global bio-feedback experiments on time scales resolving monthly to interannual variability are used to determine model sensitivity to alternative representations of solar attenuation. Model skill is evaluated for various estimates of solar attenuation to determine the cost/benefit tradeoffs and levels of effort warranted for including increasingly detailed attenuation capabilities into the Navy global ocean models.



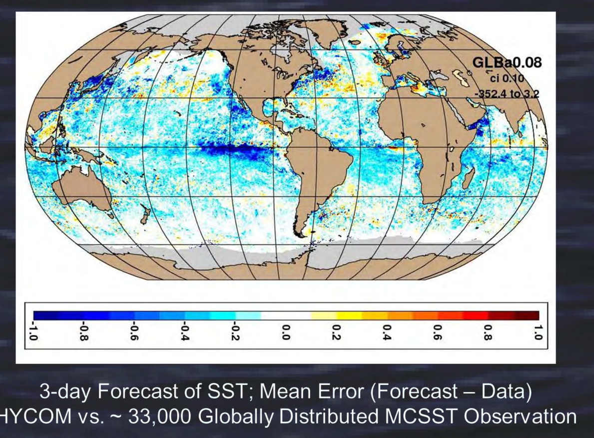
Effective Heating Layer Thickness (Z_H) Climatology for the Global Ocean

Standard implementations of HYCOM, NCOM, and operational NCOM variants (RELO, COAMPS-OS) use a Jerlov Water Type-based method to assign the penetration length scale of solar energy into the surface ocean. The method splits total shortwave solar forcing into two spectral components: long wavelengths (channel 1, red light + near infrared) and short wavelengths (channel 2, blue light and shorter wavelengths). This method originates from Paulson and Simpson [1977], which provides a two-band coefficient fit to five Jerlov 'Oceanic' Water Types. Water 'Type' however, is a rough classification system applied to a continuous field property (absorption) ranging over many orders of magnitude.

The shortwave attenuation algorithm has been upgraded to account for K-PAR depth-dependence [Lee et al., 2005]. Furthermore, the global ocean color climatology has been extended to include the entire SeaWiFS 1997-2010 record. The figure to the left shows a snapshot of the effective heating layer thickness, the layer of the upper ocean that absorbs 95% of the incident shortwave solar radiation, from monthly satellite ocean color climatology. The heating layer thickness is greatly reduced along the coasts, at the equatorial divergences, eastern margins, and at higher latitudes, largely due to the influence of phytoplankton pigment absorption and associated organic degradation materials.

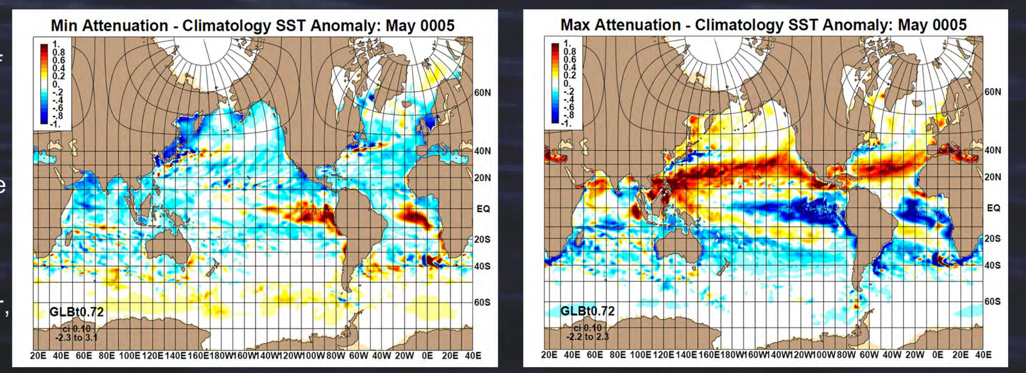
Bio-Feedback Sensitivity in the Equatorial Pacific and Globally

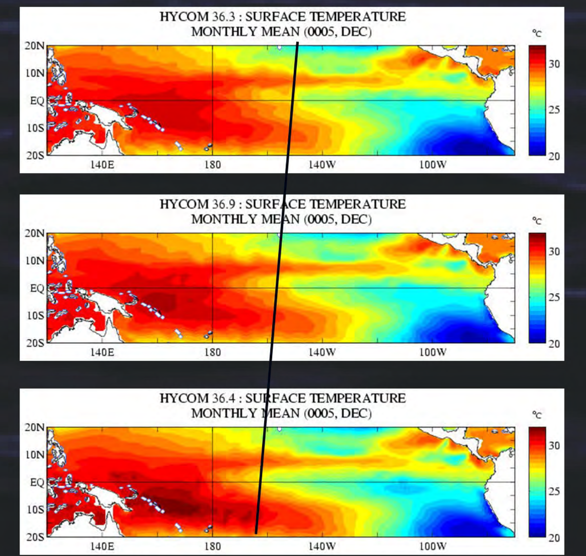
Known Bio-Feedback Sensitivity [e.g., Lengaigne et al., 2007;] Pre-Operational HYCOM Skill Metrics [Metzger et al., 2008]



3-day Forecast of SST; Mean Error (Forecast – Data) HYCOM vs. ~ 33,000 Globally Distributed MCSST Observation

Sensitivity to surface attenuation is examined in the fifth year of five-year runs of a coarse-resolution global HYCOM (500 x 382 Mercator Global Grid, 33 layers, ~0.72° resolution) forced with NCEP Climate Forecast Re-Analysis (CFSR) using the period 1993-2009 for monthly means and including with 6 hourly wind anomalies. Minimum and maximum attenuation are Jerlov type I and 9 cases. Minimum attenuation tends to cool SST globally, while maximum attenuation tends to warm SST. However, the effects are opposite in the equatorial Pacific. Over most of the ocean, increased surface attenuation tends to raise SST by trapping heat near the surface, but the warmer surface water is displaced by upwelling in the equatorial Pacific. As increased attenuation reduces heating of the subsurface water, the upwelled SST is lower.



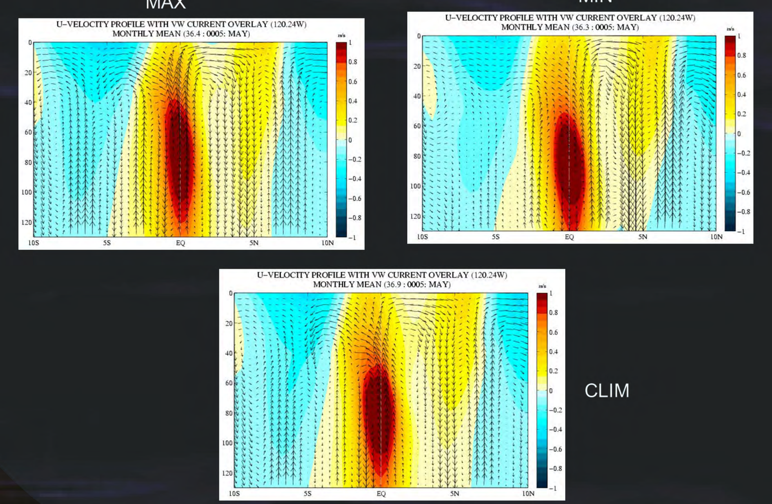


Minimum Jerlov I

Climatological

Maximum Jerlov 9

Equatorial Pacific cool tongue under conditions of minimum, climatological, and maximum surface attenuation. Maximum attenuation leads to greatest westward extent of the cool tongue. Results below show the eastward current speed in color with superimposed current vectors in the meridional/vertical plane,



Meridional Circulation Cells (5S – 5N) Contribute to Equatorial Temperature Differences

Lengaigne et al., 2007

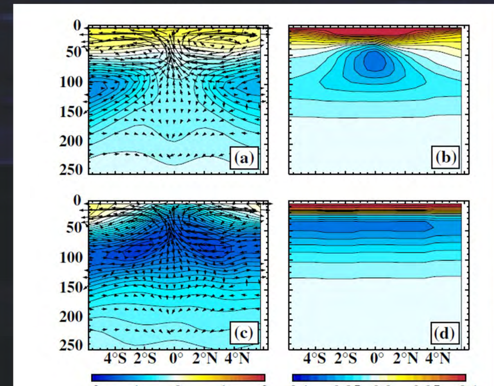


Fig. 7 Meridional sections in the eastern Pacific (6°N–6°S; 130°W–110°W) for **a** temperature differences between ChlFULL and Chl0.06 (*color*) and Chl0.06 currents (*arrows*) and **b** heating rate differences (°C month^{-1}) between ChlFULL and Chl0.06. **c**, **d** Same but for differences between Chl0.17 and Chl0.06

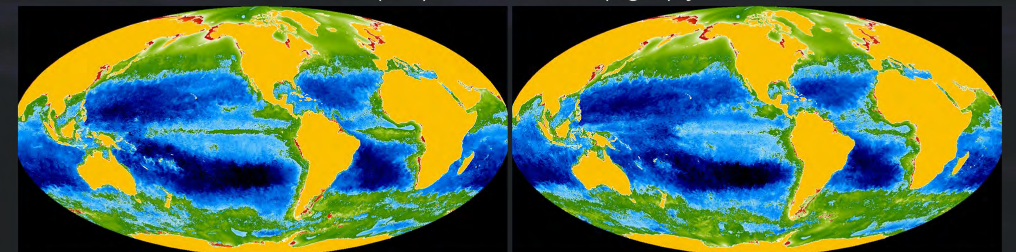
Competing Mechanisms:

Direct 1-D Heating Effect
of ↑ chl on EQ:
– Surface warm / Subsurface cool

Indirect 2-D Circulation Effect
of ↑ chl off EQ (~ 5 deg N/S):
Subsurface cooling advected to the equator via mer. Circ. EUC

The HYCOM results suggest that the circulation effect is dominant; prior published research is inconclusive.

Chlorophyll distribution identified as a representative December during a neutral ENSO (left) and El Niño (right) year



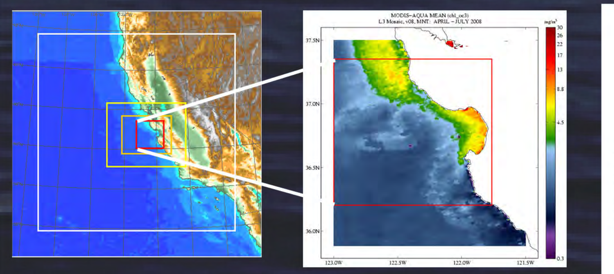
Increased equatorial upwelling increases equatorial chlorophyll and solar attenuation. Does this produce a positive feedback that increases upwelling?

Blue – Oligotrophic (0.01 – 0.2 mg m^{-3} chl);
Green – Mesotrophic (0.2 – 2 mg m^{-3} chl);
Red – Eutrophic (> 2 mg m^{-3} chl)

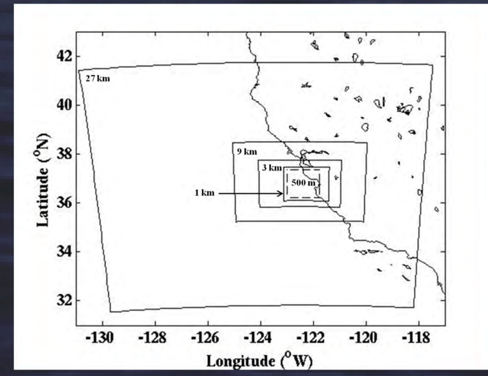
Regional COAMPS Bio-Feedback

Bio-feedback within regional domains is represented within the Coupled Ocean-Atmosphere Prediction System (COAMPS) on spatial scales of 3 km and less and temporal scales from hours to days. Our studies show how the spatial and temporal bio-optical variability impacts the coupled modeling system.

COAMPS-OS two-way coupled source code (NCOM) was modified to use attenuation length scales based on satellite ocean color data (MODIS). Sensitivity experiments in the vicinity of Monterey Bay are conducted within a series COAMPS atmospheric nests. The innermost atmospheric nest (1 km) forces wave and ocean COAMPS implementations configured on a 500 m grid. Experiments over April-July 2008 examine the wave and ocean sensitivity to representation of surface attenuation (Jerlov IA or chlorophyll estimates from MODIS) and modifications to the surface shortwave radiation [Jolliff et al., in press].

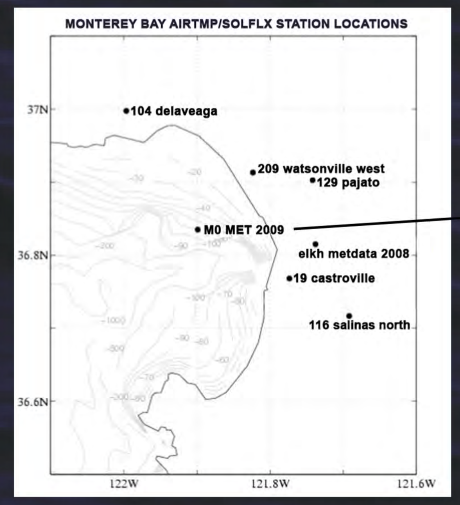


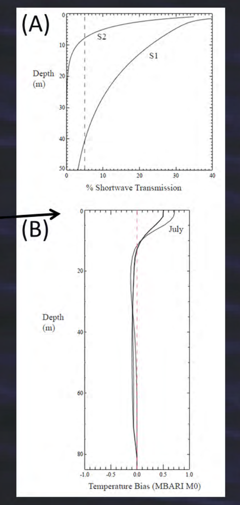
Inserting satellite ocean color data (right) into the COAMPS-OS nested two-way coupled ocean/atmosphere modeling system (left).

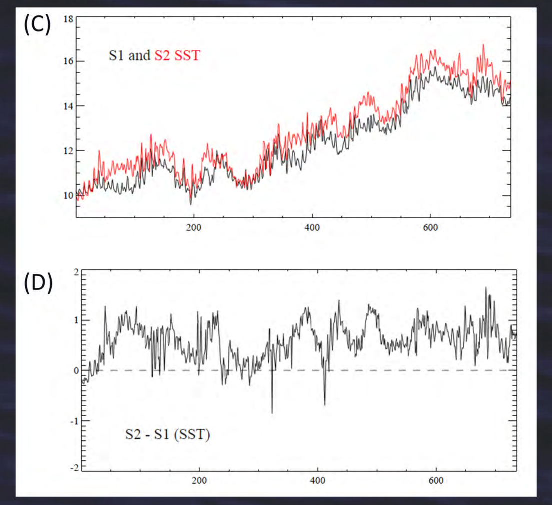


- Horizontal Resolution:
  - Atmos: 27, 9, 3, and 1 km
  - Ocean: 500 m
  - Wave: 500 m
- Vertical Resolution:
  - 60 atmospheric levels
  - 50 ocean levels
- Boundary Conditions:
  - Atmos: 1° NOGAPS
  - Ocean: 1/8° Global NCOM
- Data Assimilation:
  - Atmos: NAVDAS (3DVAR)
  - Ocean: NCODA (3DVAR)
  - 12-hour update cycle
- ESMF forcing:
  - Atmos: SST
  - Ocean: MSLP, wind stress, heat & moisture fluxes, shortwave radiation
  - Wave: 10 m wind, Stokes' Drift, Wave Rad. Stress Grad.

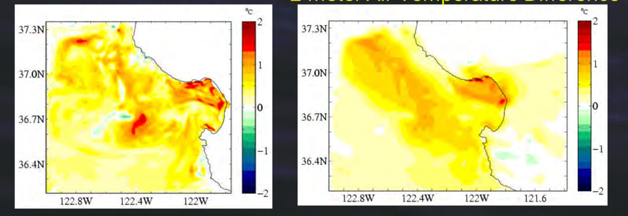
Figure A (top middle right) indicates the percent penetration of shortwave radiation as a function of depth, while figure B (bottom middle right) shows the reduced temperature bias in control S1 (bold) compared to the bias in S2, where bias is relative to the unassimilated profile of buoy observations. Figure C (top far right) follows the warmer S2 SST as function of experiment day, while Figure D (bottom far right) is the time series of S2-S1 SST. Sensitivity to attenuation is revealed by differences between a control case (S1) using default constant Jerlov IA attenuation and a case (S2) with a realistically varying attenuation field based on MODIS observations of chlorophyll concentration. Stations with meteorological observations are indicated with the blue labels.





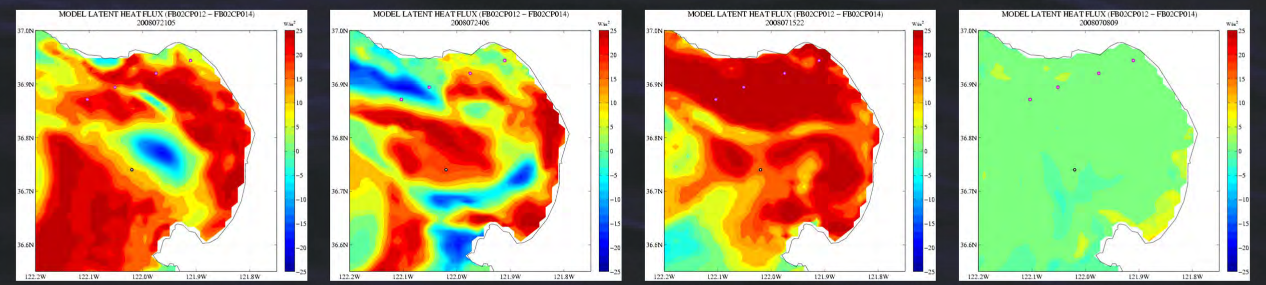


Resolving Bio-Optical Feedbacks to Ocean/Atmosphere Dynamics



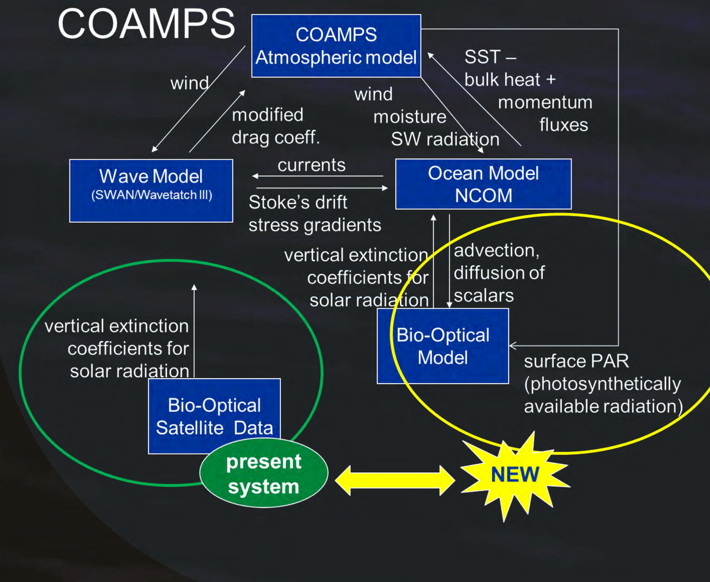
Positive temperature bias (relative warming) for the upper ocean and lower atmosphere is simulated when COAMPS-OS ingests satellite bio-optical data.

The inner ocean and atmosphere COAMPS-OS nests were run in data assimilative mode for 1 month, and then in free-run mode for the ocean model for the following 3 months (May – July). During this latter part of the simulation, the COAMPS model with optics developed a warm bias in SST and air temperature at 2 m. The bias is due to the ocean model simulating the biological "heat trapping" effect: the additional near-surface absorption of radiant energy from phytoplankton blooms in Monterey Bay results in elevated SSTs. The additional thermal energy at the ocean surface then fluxes back into the lower atmosphere, producing a warming effect. Latent heat flux from the ocean to the atmosphere (positive) increased by an average 43% in the July COAMPS simulation including satellite bio-optical data. Selected snapshots of hourly latent heat flux bias (case S2-S1, i.e., MODIS-Jerlov IA) are below.



Monterey Bay, California; COAMPS-OS Latent Heat Flux Difference Field (July; hourly): [COAMPS(MODIS)] – [COAMPS (Jerlov IA)]

Future plans include replacing the bio-optical satellite data with a bio-optical forecast model.



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