Simulation of Hydrodynamics and Water Quality for Chesapeake Bay in a Projected Climate Condition

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STAC Review on WQSTM

June 5, 2017

●Purpose: Chesapeake Bay TMDL requires to estimate the impact of water quality by climate changes.

● Method: use CH3D-ICM hydrodynamic and water quality model.

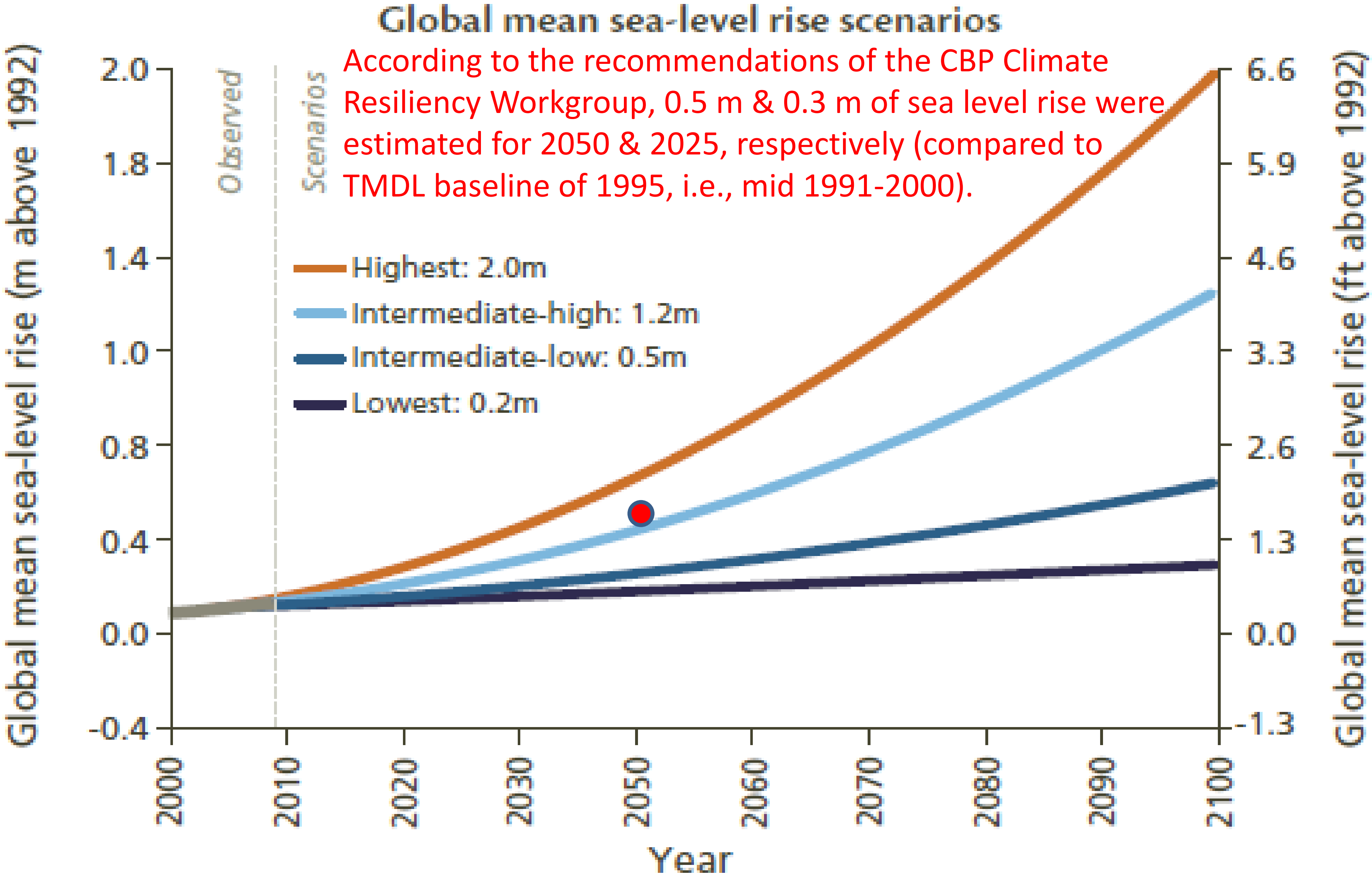
1) A projected climate condition in 2050 (&2025, etc.), considering

A) Sea level rise (SLR);

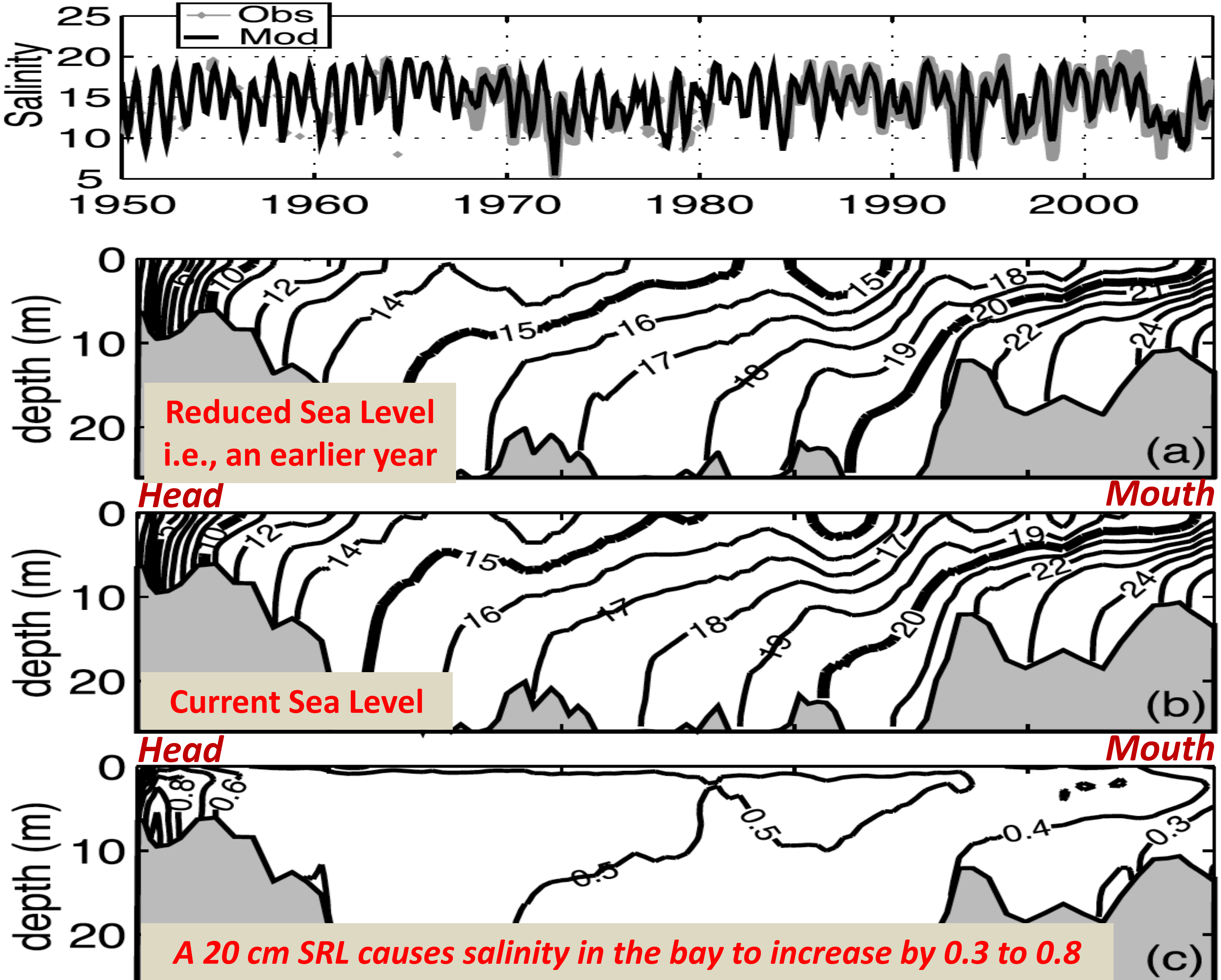
B) Temperature increase (Global Warming).

SLR and temperature increase will modify circulation, stratification, and WQ.

2) Model simulation Period: 1991-2000, because WQ in the 1991-2000 average condition has been used for Bay's TMDL evaluation. Thus, we will run 1991-2000 in modified, delta, conditions of Water Surface Elevation and Air Temperature.

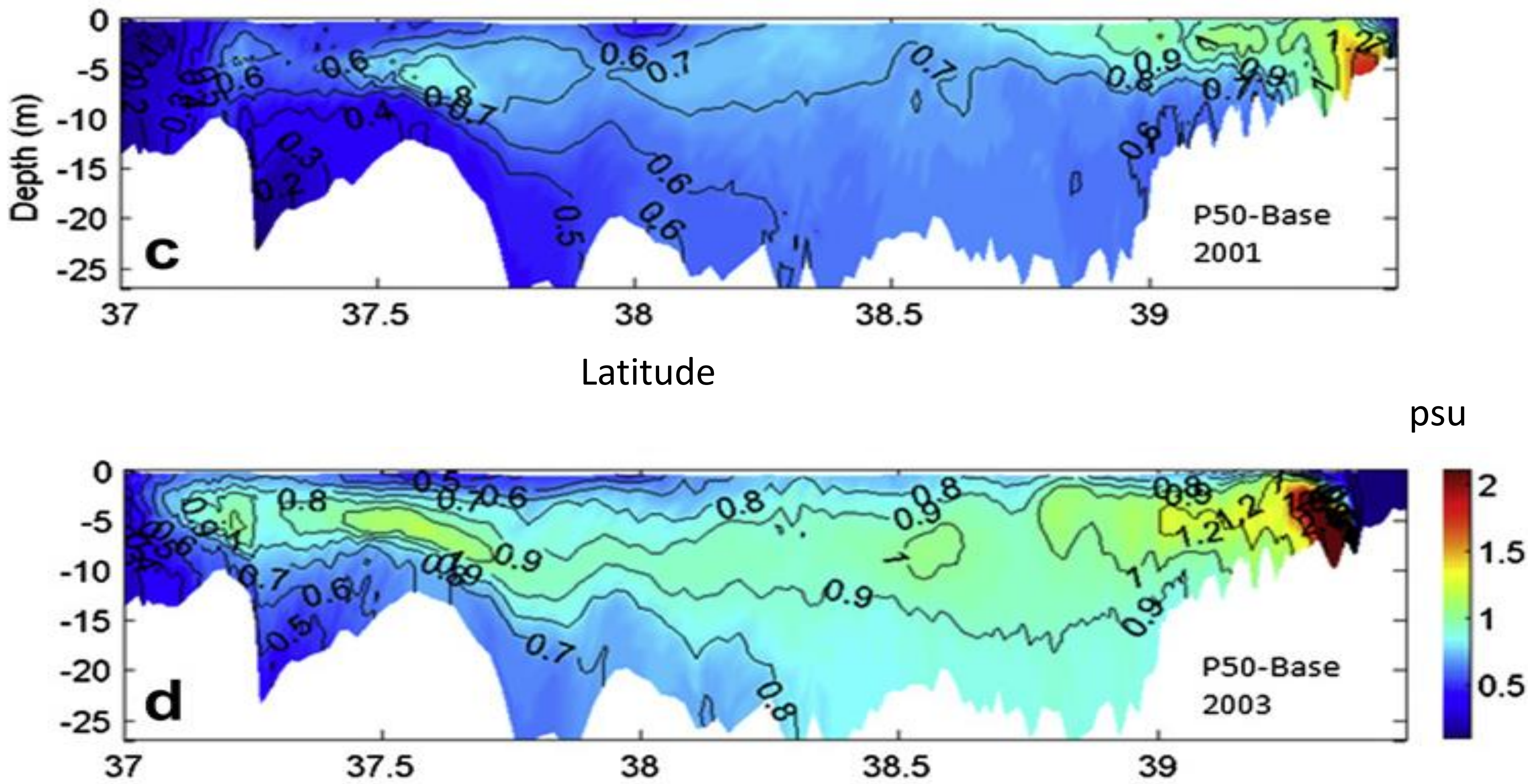


From Parris, A. et al. (2012). *Global Sea Level Rise Scenarios for the United States National Climate Assessment. NOAA Technical Report OAR CPO-1. National Oceanic and Atmospheric Administration, Silver Spring, Maryland.*



From T. W. Hilton, R. G. Najjar, L. Zhong, and M. Li (2009)

Salinity difference between P50 and Base



Bay mouth Latitude Bay head

P50: 50 cm Sea Level Rise

From Hong and Shen (2012)

The 3-D salinity fields (due to circulation) are computed:

$$\frac{\partial hS}{\partial t} = \frac{E_v}{Pr_v}\frac{\partial}{\partial z}\left(K_v\frac{\partial S}{\partial z}\right) - R_o\left(\frac{\partial huS}{\partial x} + \frac{\partial hvS}{\partial y} + \frac{\partial hwS}{\partial z}\right)$$

$$+ \frac{E_H}{Pr_H}\left[\frac{\partial}{\partial x}\left(K_H\frac{\partial hS}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_H\frac{\partial hS}{\partial y}\right)\right]$$

Where, S =salinity; h = thickness;

u, v, w = x, y, z component of velocity

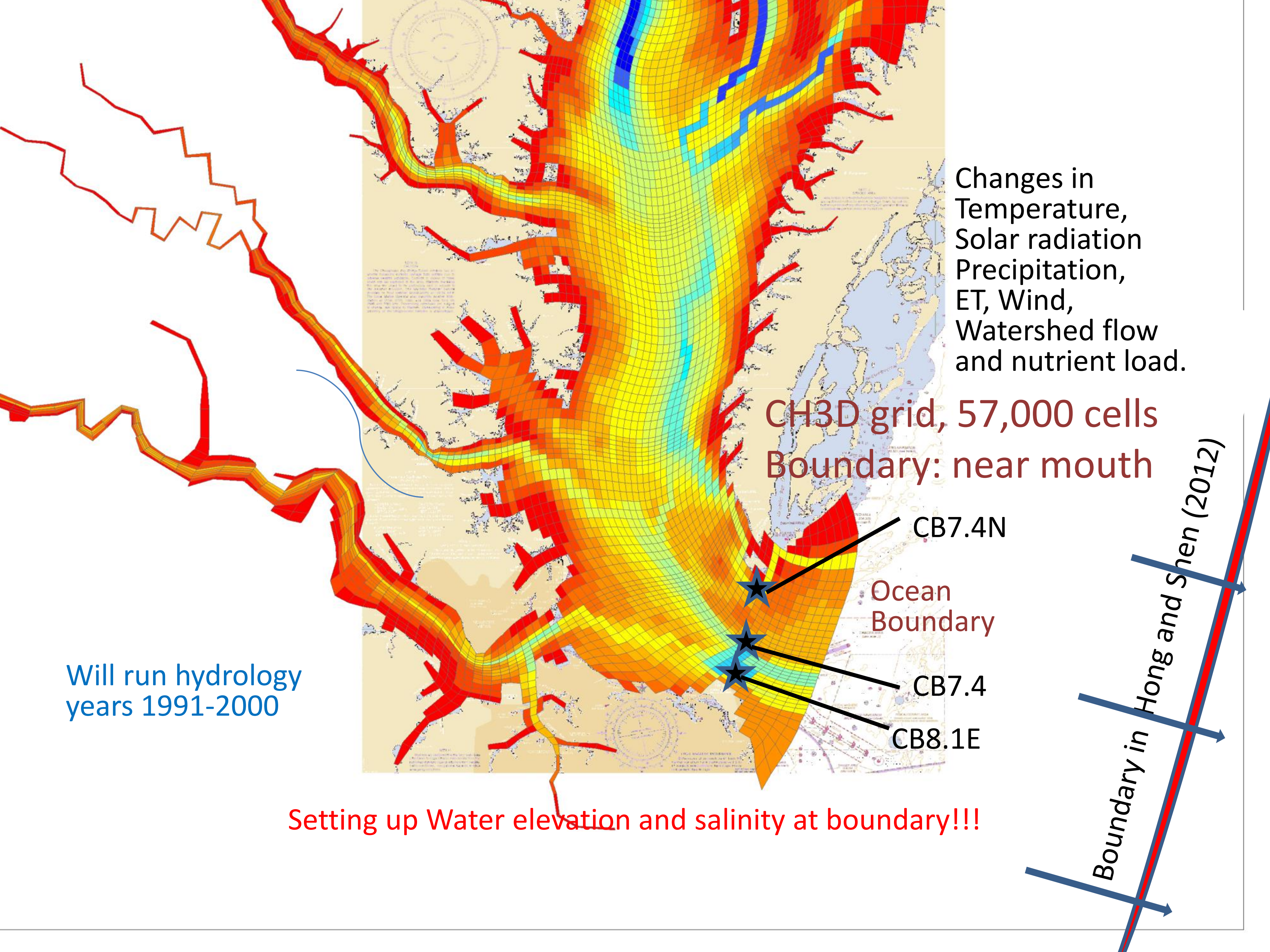
R_o= Rossby number

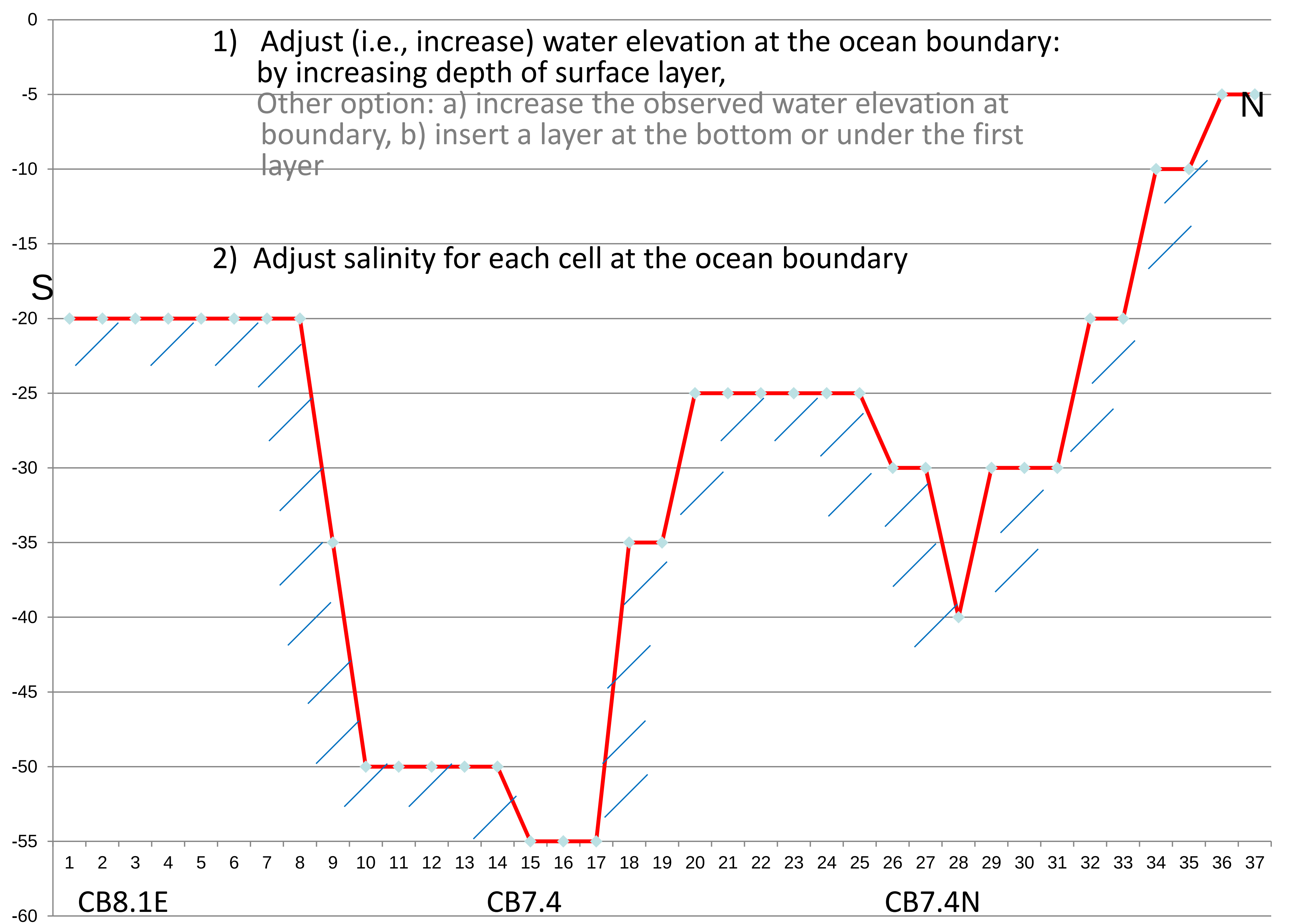
K= turbulent eddy coefficients (horizontal or vertical: $_{H,\ v}$)

E = Ekman number (horizontal or vertical: $_{H,\ v}$)

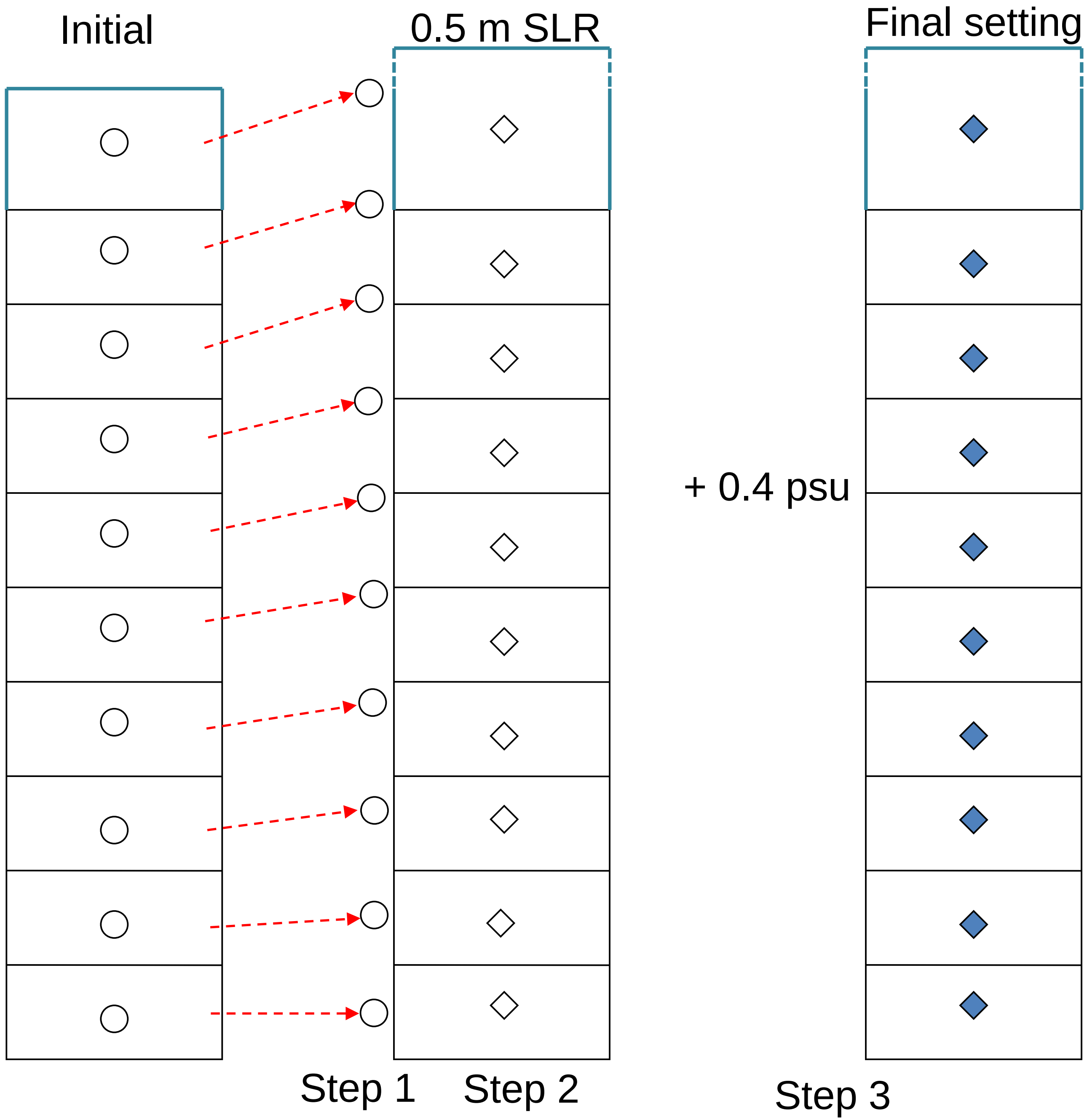
Pr= Prandtl number (horizontal or vertical: $_{H,\ v}$)

While the salinity at the ocean boundary are based on the observed at CBP station.

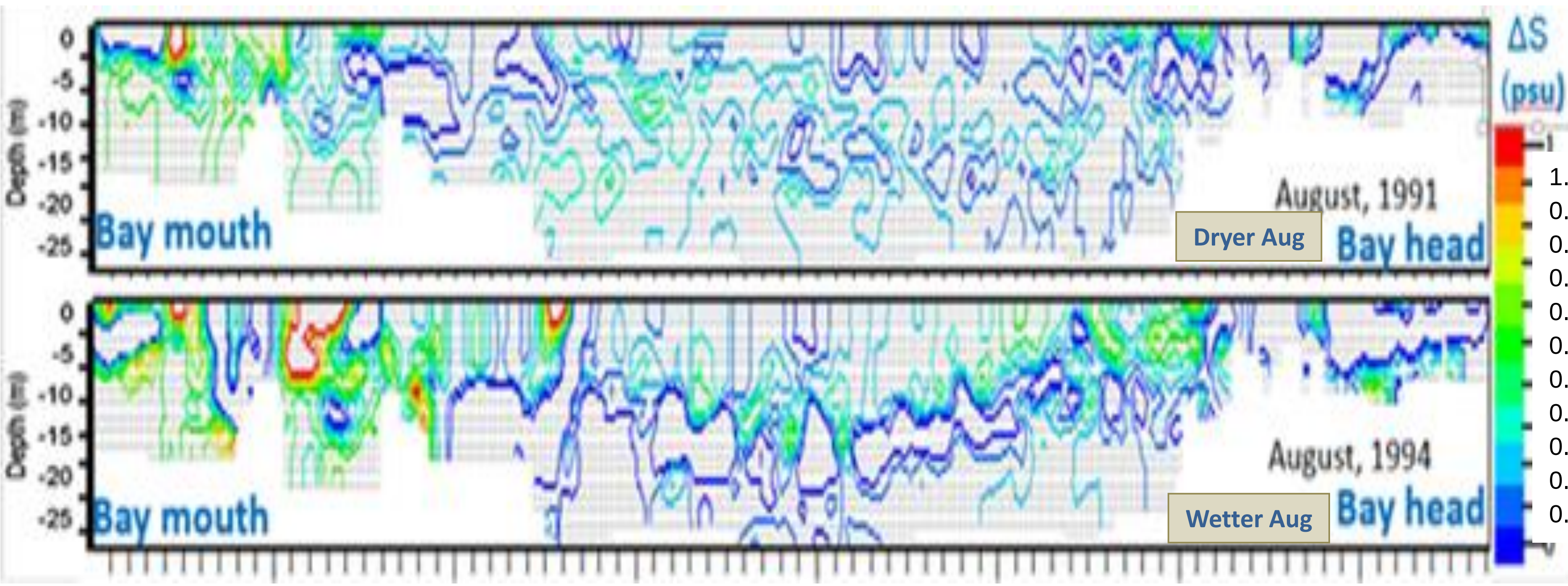

Changes in
Temperature,
Solar radiation
Precipitation,
ET, Wind,
Watershed flow
and nutrient load.
CH3D grid, 57,000 cells
Boundary: near mouth
CB7.4N
Ocean
Boundary
CB7.4
CB8.1E
Will run hydrology
years 1991-2000
Setting up Water elevation and salinity at boundary!!!
Boundary in Hong and Shen (2012)


1) Adjust (i.e., increase) water elevation at the ocean boundary:
by increasing depth of surface layer,
Other option: a) increase the observed water elevation at boundary, b) insert a layer at the bottom or under the first layer
2) Adjust salinity for each cell at the ocean boundary
S
N
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
CB8.1E
CB7.4
CB7.4N

Boundary salinity setting

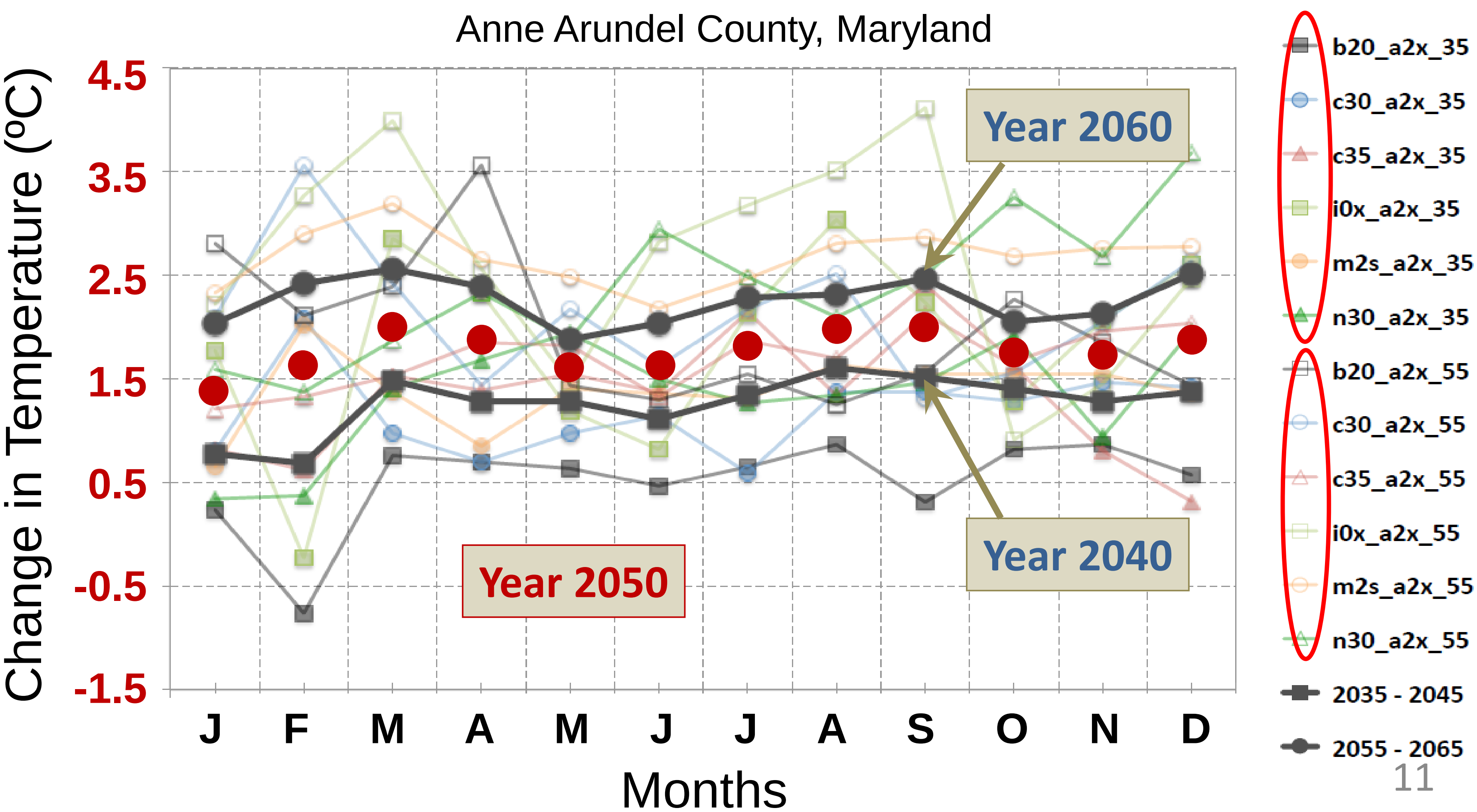


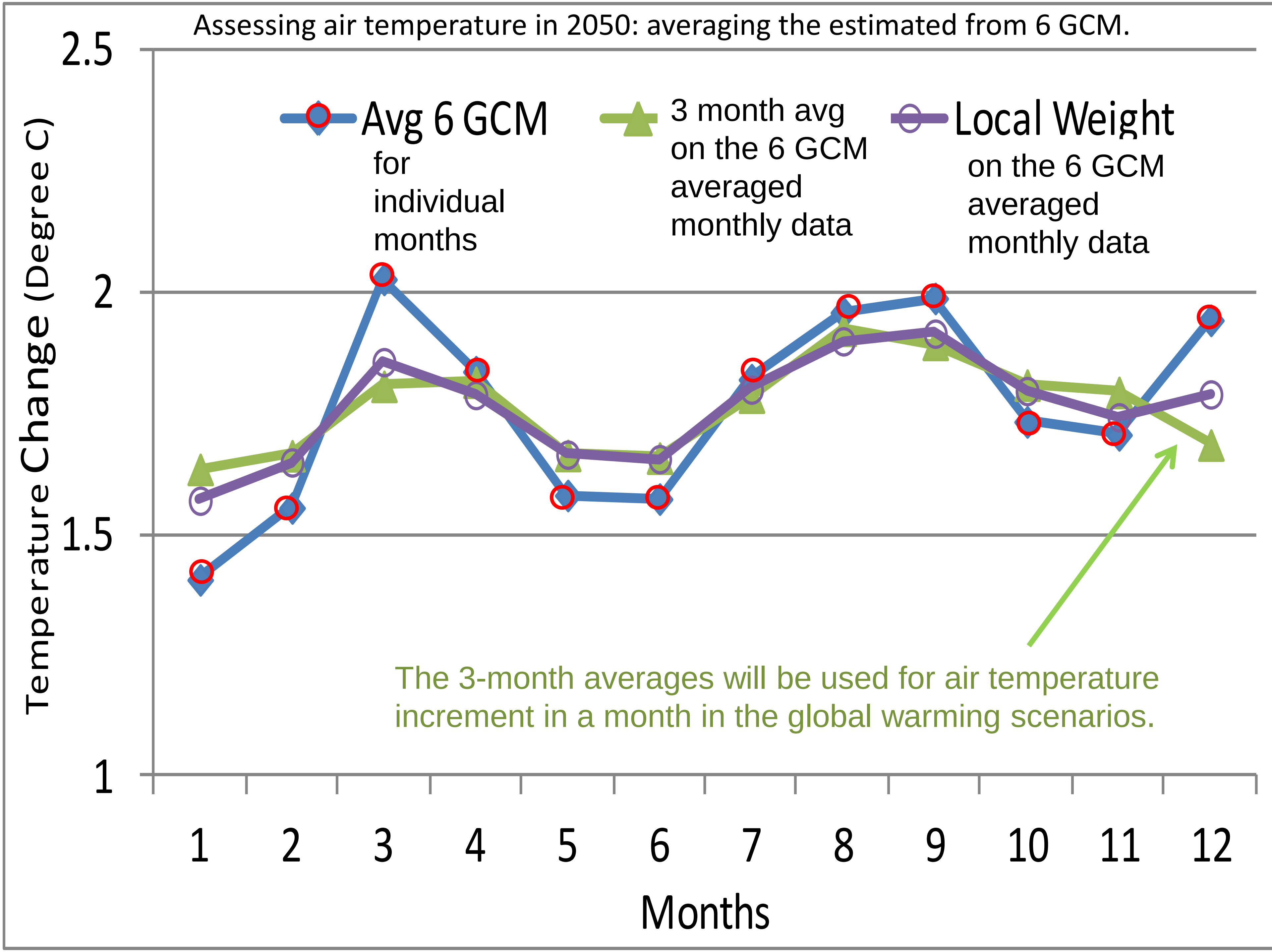
Salinity difference between 2050 SLR and the Baseline



2050 Temperature Increase Scenario

Projections of downscaled ***mean monthly change in temperature*** were obtained from multiple global climate models –




Assessing air temperature in 2050: averaging the estimated from 6 GCM.
Avg 6 GCM
for individual months
3 month avg on the 6 GCM averaged monthly data
Local Weight
on the 6 GCM averaged monthly data
The 3-month averages will be used for air temperature increment in a month in the global warming scenarios.
Temperature Change (Degree C)
2.5
2
1.5
1
1
2
3
4
5
6
7
8
9
10
11
12
Months

The 3-D Temperature fields (due to circulation) are computed:

$$\frac{\partial hT}{\partial t} = \frac{E_v}{Pr_v}\frac{\partial}{\partial z}\left(K_v \frac{\partial T}{\partial z}\right) - R_o\left(\frac{\partial huT}{\partial x} + \frac{\partial hvT}{\partial y} + \frac{\partial hwT}{\partial z}\right)$$

$$+ \frac{E_H}{Pr_H}\left[\frac{\partial}{\partial x}\left(K_H \frac{\partial hT}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_H \frac{\partial hT}{\partial y}\right)\right]$$

Where, T =water temperature

h = thickness

u, v, w = x, y, z component of velocity

R_o= Rossby number

K= turbulent eddy coefficients (horizontal or vertical: $_{H,\,v}$)

E = Ekman number (horizontal or vertical: $_{H,\,v}$)

Pr= Prandtl number (horizontal or vertical: $_{H,\,v}$)

2. Simulation of Water Temperature due to Global Warming

A) Water temperature will increase due to air temperature increase: through heat exchange between air and the water, as simulated in CH3D:

$$\partial T_w / \partial z = Pr / Ev \times K (T_a - T_e)$$

Where, Tw: water temperature; Ta: air temperature

Z: depth

Te: Equilibrium temperature

K: surface heat exchange coefficient

Ev: vertical Ekman number

Pr: Prandtl number

In order to simulate Tw in 2050, we calculated Te and K in 2050 which is a function of Ta in 2050, assuming no change in humidity and wind.

2. Simulation of Water Temperature due to Global Warming

A) Water temperature will increase due to air temperature increase: through heat exchange between air and the water, as simulated in CH3D:

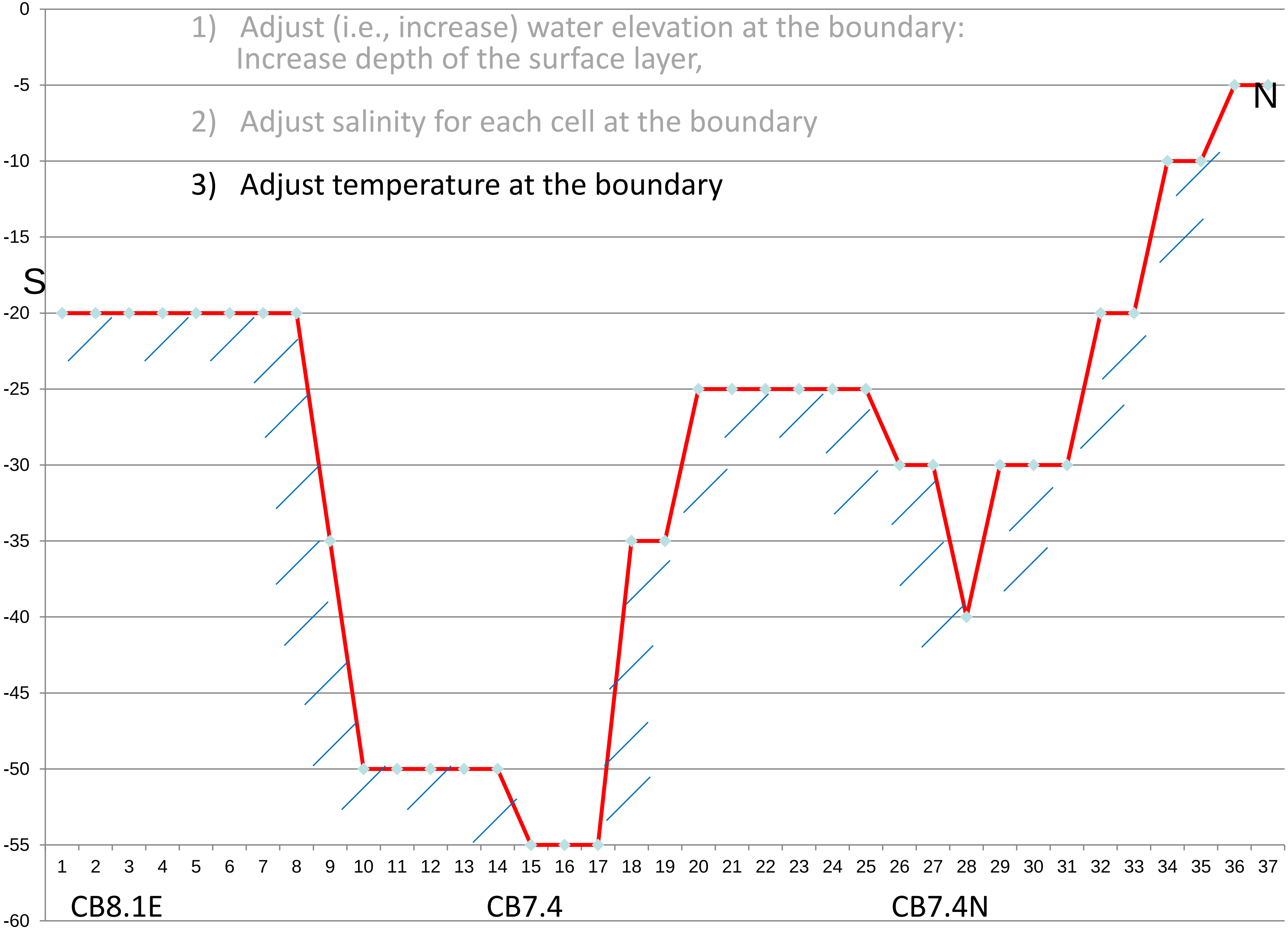
$dTw / dz = Pr / Ev \times K (T - Te)$

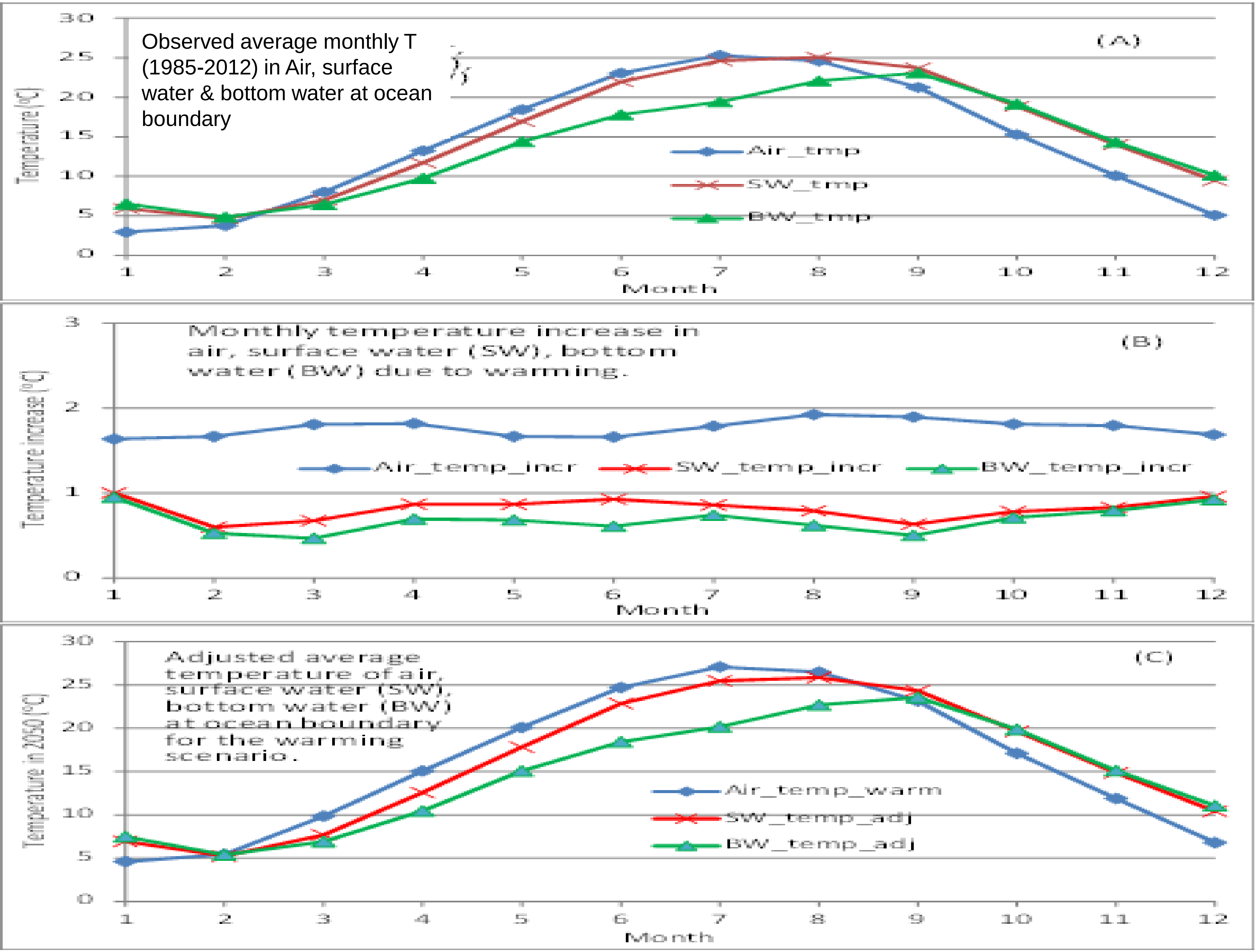
Where, Tw: water temperature, Ta: air temperature
Z: depth
Te: Equilibrium temperature
K: surface heat exchange coefficient
Ev: vertical Ekman number
Pr: Prandtl number

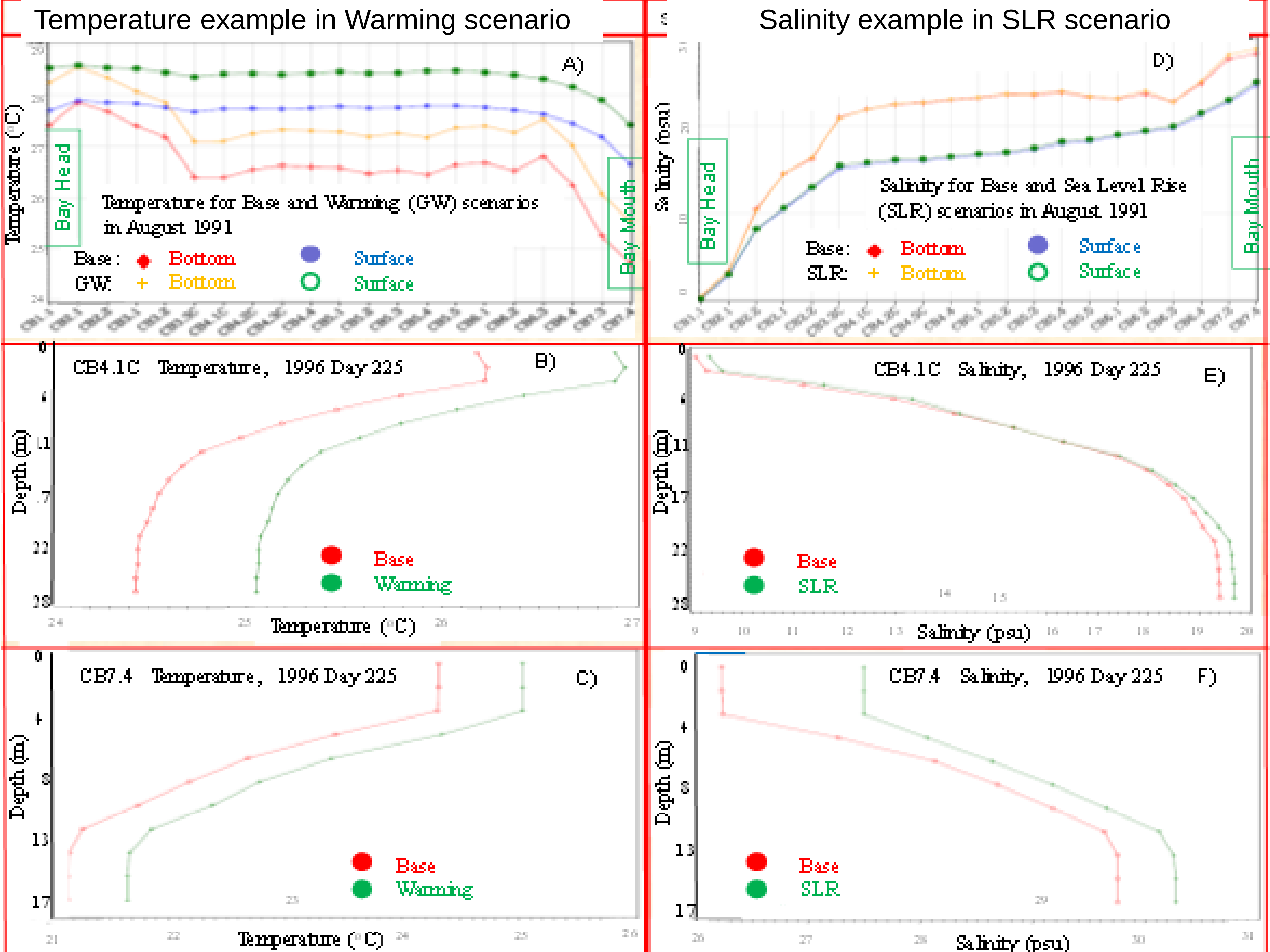
In order to simulate Tw in 2050, we calculated Te and K in 2050 which is a function of Ta in 2050, assuming no changes in humidity and wind.

B) The Tw at the boundary and river inputs also influence the Bay's Tw.

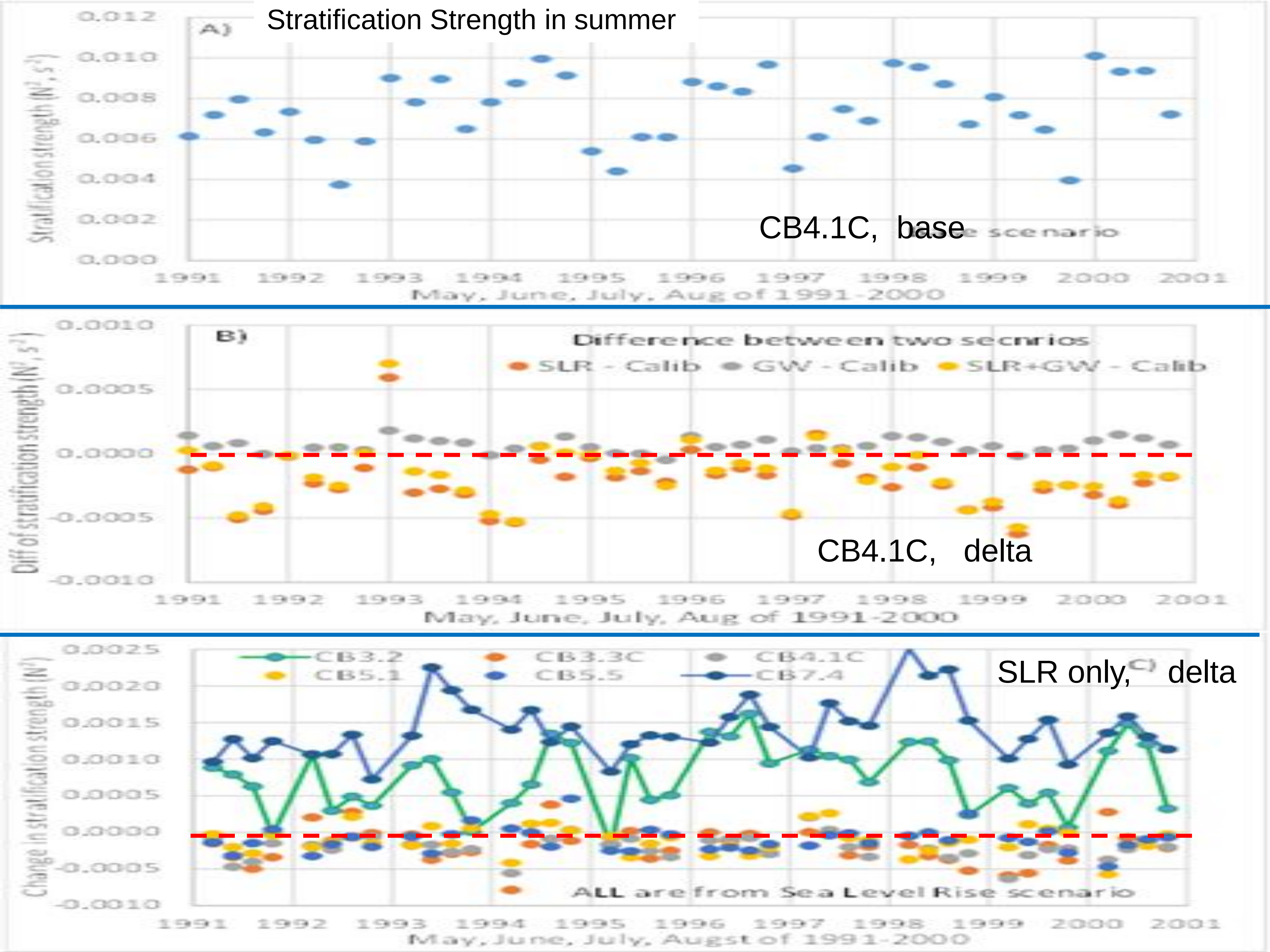
* Estimate and set Tw at the ocean boundary in 2050 condition.
* Estimate and set Tw for river discharges in 2050 condition.


1) Adjust (i.e., increase) water elevation at the boundary:
Increase depth of the surface layer,
2) Adjust salinity for each cell at the boundary
3) Adjust temperature at the boundary
S
N
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
CB8.1E
CB7.4
CB7.4N


Observed average monthly T (1985-2012) in Air, surface water & bottom water at ocean boundary
(A)
Air_tmp
SW_tmp
BW_tmp
Temperature [°C]
Month
Monthly temperature increase in air, surface water (SW), bottom water (BW) due to warming.
(B)
Air_temp_incr
SW_temp_incr
BW_temp_incr
Temperature increase [°C]
Month
Adjusted average temperature of air, surface water (SW), bottom water (BW) at ocean boundary for the warming scenario.
(C)
Air_temp_warm
SW_temp_adj
BW_temp_adj
Temperature in 2050 [°C]
Month

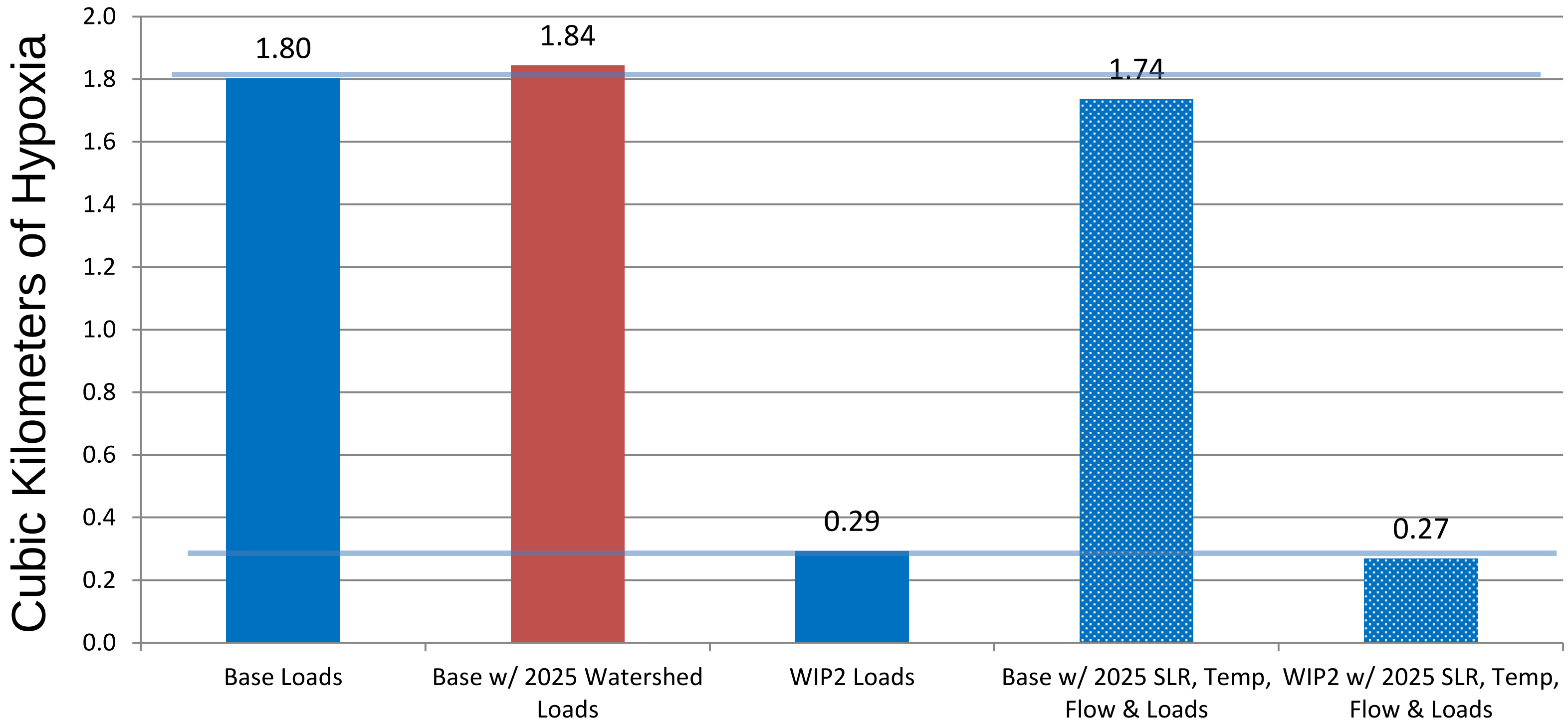


Temperature example in Warming scenario
Salinity example in SLR scenario
A)
Temperature (°C)
Bay Head
Bay Mouth
Temperature for Base and Warming (GW) scenarios in August 1991
Base: Bottom Surface
GW: Bottom Surface
D)
Salinity (psu)
Bay Head
Bay Mouth
Salinity for Base and Sea Level Rise (SLR) scenarios in August 1991
Base: Bottom Surface
SLR: Bottom Surface
B)
CB4.1C Temperature, 1996 Day 225
Depth (m)
Base
Warming
Temperature (°C)
E)
CB4.1C Salinity, 1996 Day 225
Depth (m)
Base
SLR
Salinity (psu)
C)
CB7.4 Temperature, 1996 Day 225
Depth (m)
Base
Warming
Temperature (°C)
F)
CB7.4 Salinity, 1996 Day 225
Depth (m)
Base
SLR
Salinity (psu)



Stratification Strength in summer
A)
Stratification strength (N², s⁻²)
0.012
0.010
0.008
0.006
0.004
0.002
0.000
CB4.1C, base
scenario
1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001
May, June, July, Aug of 1991-2000
B)
Difference between two secnrios
SLR - Calib
GW - Calib
SLR+GW - Calib
Diff of stratification strength (N², s⁻²)
0.0010
0.0005
0.0000
-0.0005
-0.0010
CB4.1C, delta
1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001
May, June, July, Aug of 1991-2000
CB3.2
CB3.3C
CB4.1C
CB5.1
CB5.5
CB7.4
SLR only, C) delta
Change in stratification strength (N²)
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
-0.0005
-0.0010
ALL are from Sea Level Rise scenario
1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001
May, June, July, Augst of 1991-2000

A counterintuitive result: Why does hypoxia decrease under estimated under 2025 temperature, precipitation, and sea level despite higher estimated watershed loads?

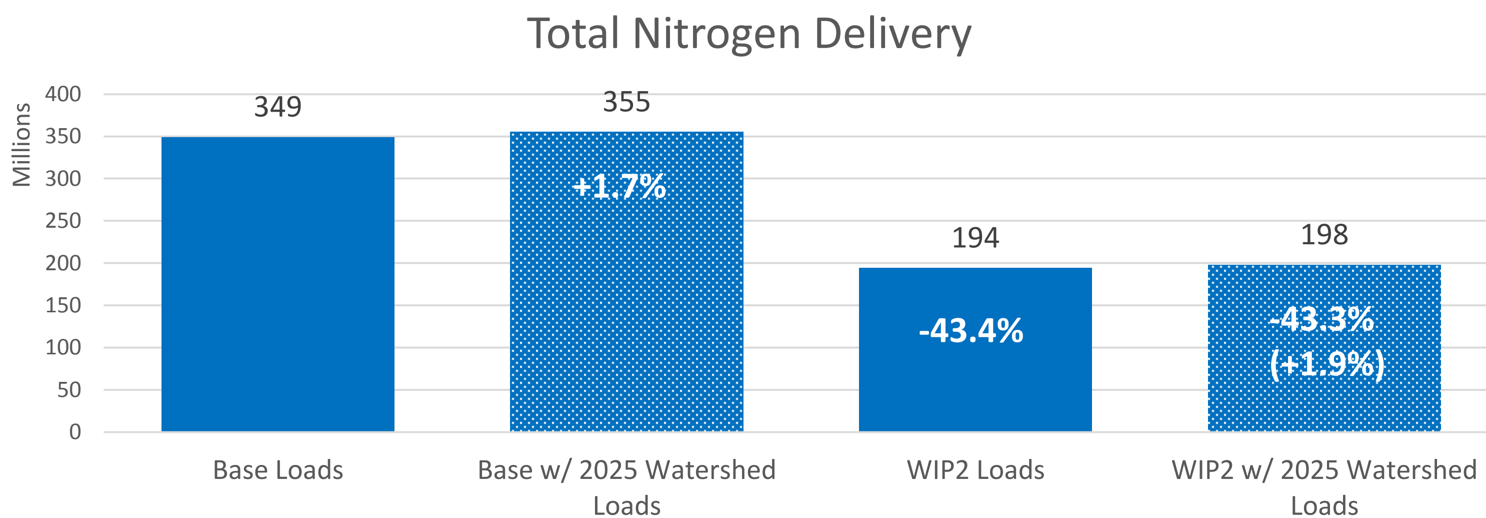


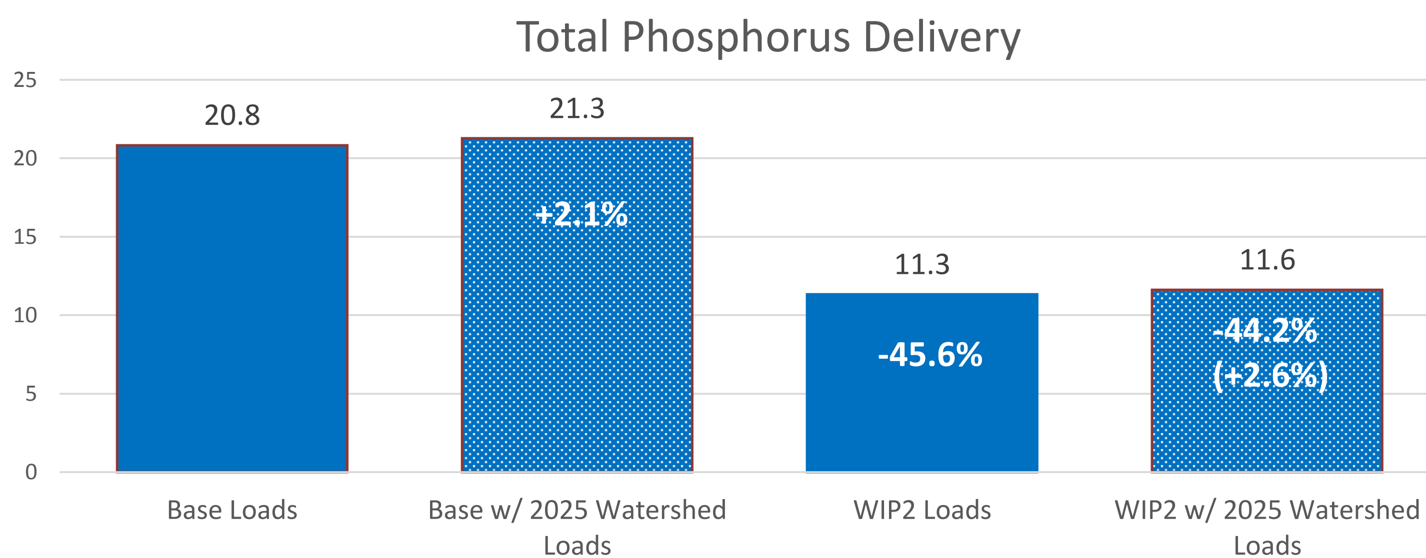
DO <1 mg/l annual average daily hypoxia from 1991 to 2000 over the summer hypoxic season of May through September.

solid blue = key scenario, solid red = sensitivity scenario, stippled blue = 2025 climate

Watershed loads are estimated to increase by about 2% under estimated 2025 climate conditions compared to 1995 conditions.

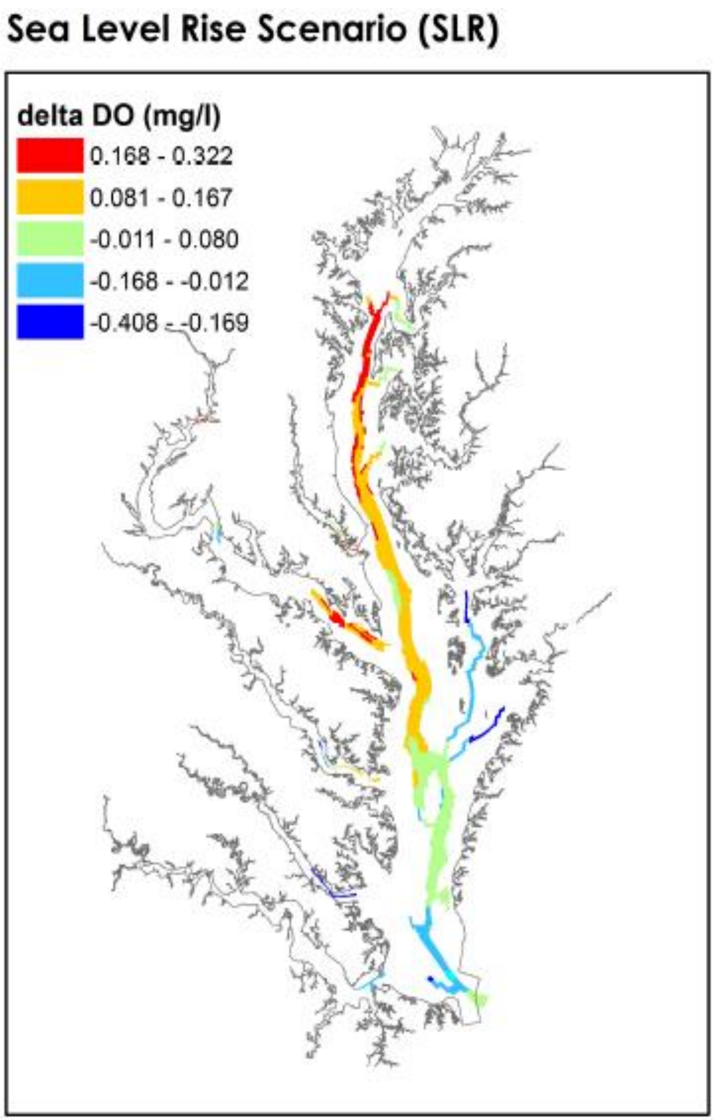
Percent change from Base Loads except for (% change in WIP loads under 2025 conditions).





Gopal Bhatt, December 2016 Quarterly Review

Influence of Estimated 2050 Sea Level Rise (0.5 m) on Bottom DO



The influence of an 2050 estimated sea level rise on Chesapeake hypoxia is significant.

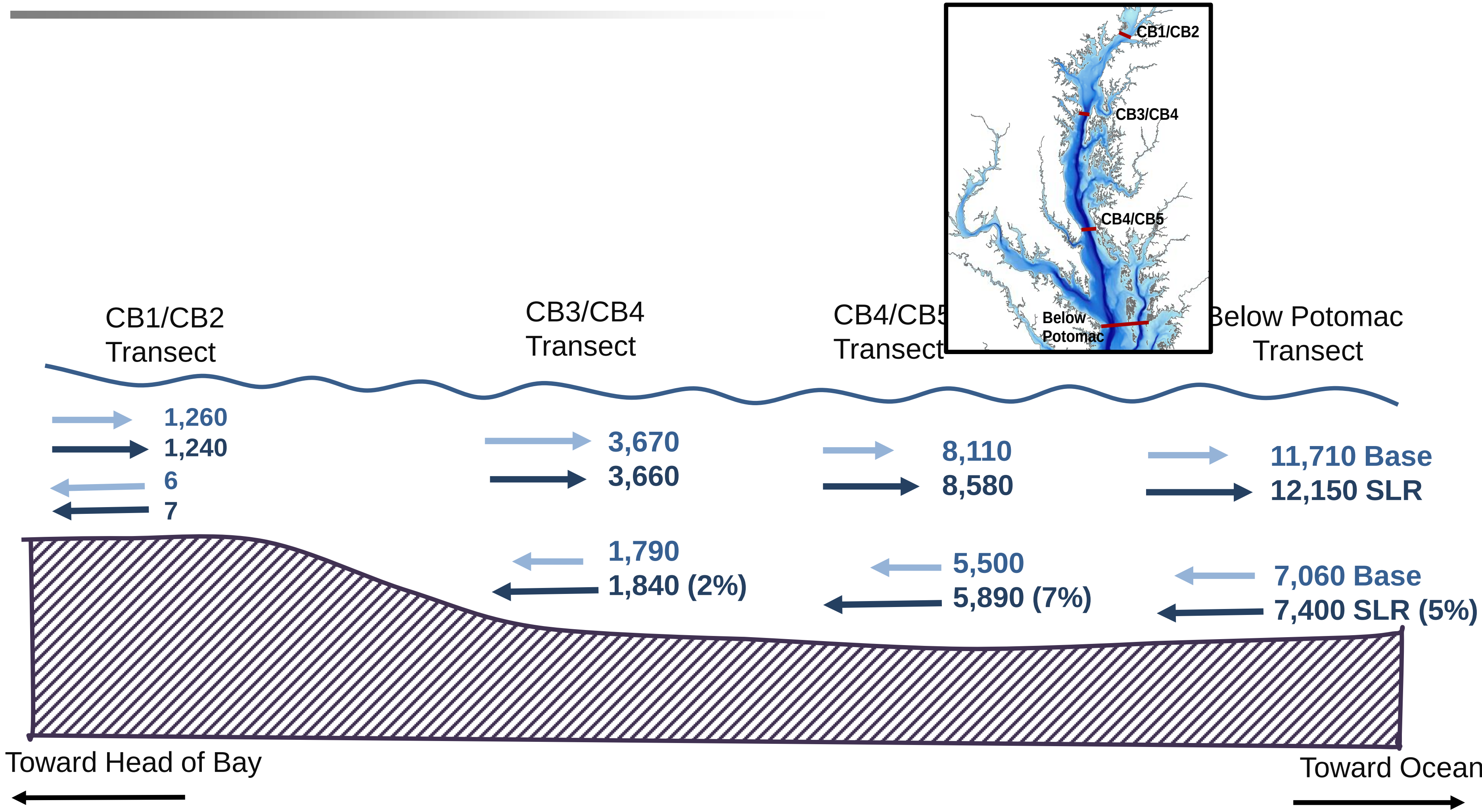
The estimated change from the base (1991 to 2000) condition in Chesapeake hypoxia due to 2050 estimated sea level rise conditions ranges from 0.3 mg/l to -0.4 mg/l.

Hypoxia decreases in the mid-Bay are due to increased ventilation of deep Chesapeake waters by well oxygenated ocean waters and also because of decreases in vertical stratification in mid-Bay.

The estimated 2025 (0.3 m) sea level rise increases also has a slightly positive influence on water quality standard achievement.

Source: CERF Conference 2015

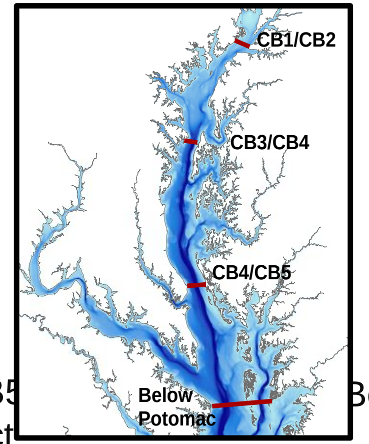
Cross-transect water mass fluxes (m³/s) : Base Case versus Sea Level Rise Scenario

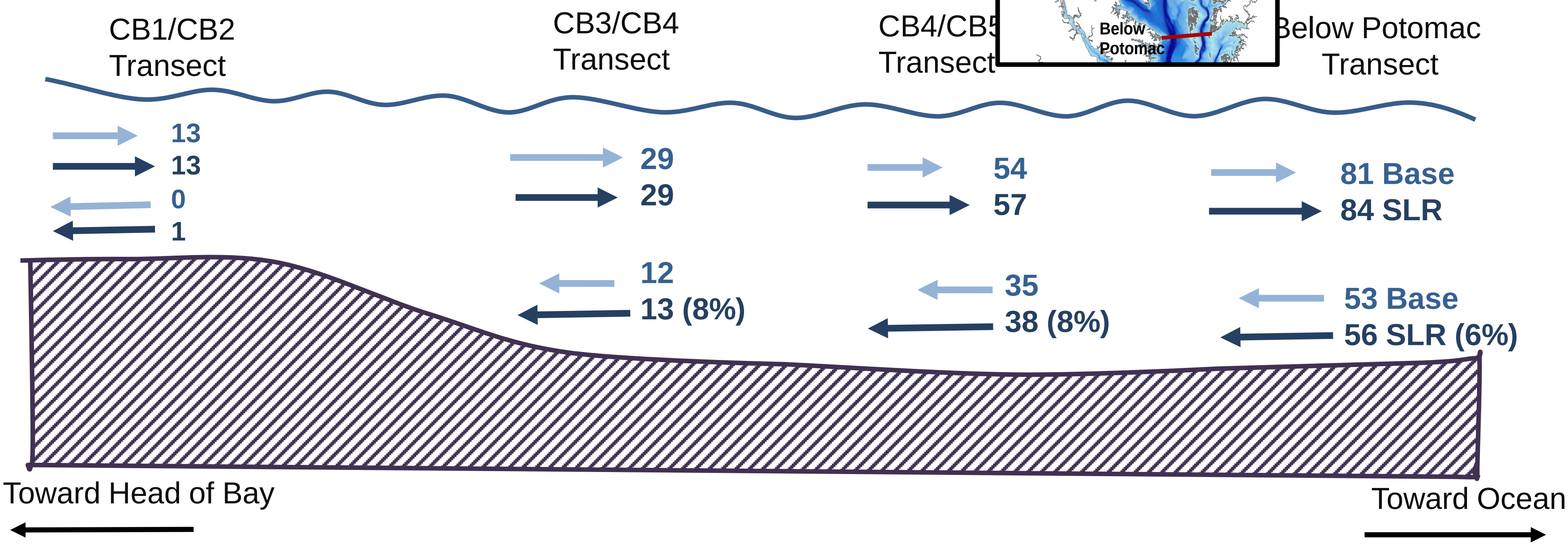


Base = Beta 4 Calibration. SLR = 0.3m Sea Level Rise Scenario representing relative Chesapeake sea level rise from 1995 to 2025. Units in mean cubic meters per second (m^3/s) for 1991 to 2000 hydrodynamics.

Cross-transect DO fluxes (kg/s): Base Case versus Sea Level Rise (SLR) Scenario

To put into context, 3.2 kg/sec of O_2 delivered to bottom waters at the edge of the deep water channel (Below Potomac Transect) is equivalent to delivering the volume of air in a box larger than 1 kilometer long, 1 kilometer wide, and 1 kilometer tall each day.





Base = Beta 4 Calibration. SLR = 0.3m Sea Level Rise Scenario representing relative Chesapeake sea level rise from 1995 to 2025. Units in mean kg DO per second (m^3/s) for 1991 to 2000 hydrodynamics.

Conclusions

- This is a work in progress using the Beta 3 Watershed Model input loads and the Beta 4 WQSTM to provide the best estimate available today. Need to run the analysis on the final Watershed and WQSTM models.
- The CBP Modeling Workgroup is factoring into the Chesapeake Bay assessment tools the latest research on climate change with guidance from the STAC and the Climate Resiliency Workgroup.
- The estimated 2025 and 2050 sea level rise has a small but positive influence on Chesapeake hypoxia.
- The estimated 2025 temperature increase has a negative influence on Chesapeake hypoxia and on Chesapeake water quality standards (WQS).

Conclusions *(continued)*

- The CH3D Model has a reasonable setup and decision rules to model conditions simulating estimated temperature increase and sea level rise under future climate conditions.
- The model reasonably simulates responses in temperature and salinity, estuarine circulation, stratification, chlorophyll-a, water clarity, and dissolved oxygen due to climate change.
- Future work is oriented toward developing a range of climate change estimates to reflect different assumptions of rainfall intensity for 2025 estimates and different future estimated greenhouse gas concentrations (Representative Concentration Pathways (RCPs)) for 2050.