Changes in the Mixing Regime of Crater Lake in a Future Climate

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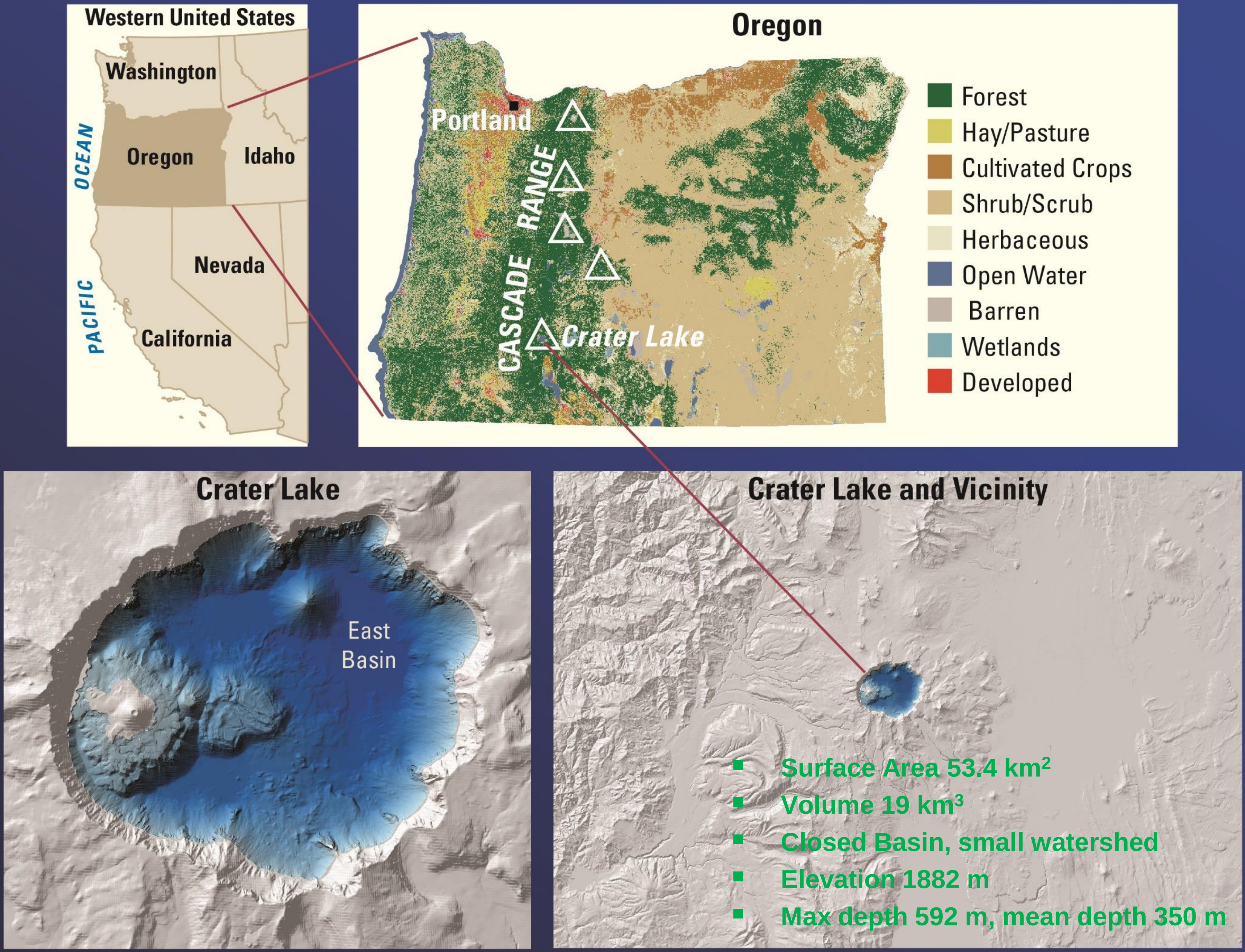
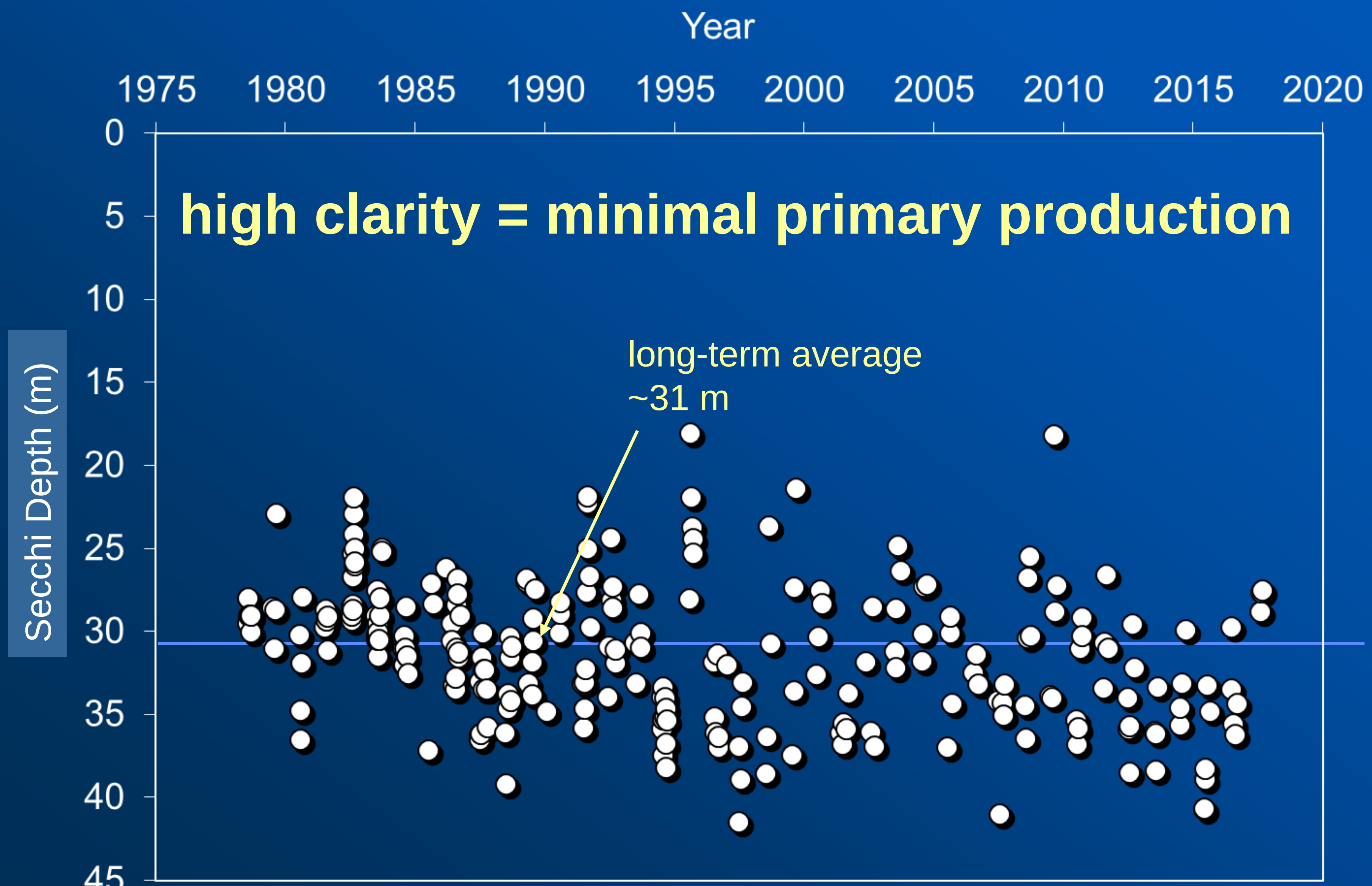


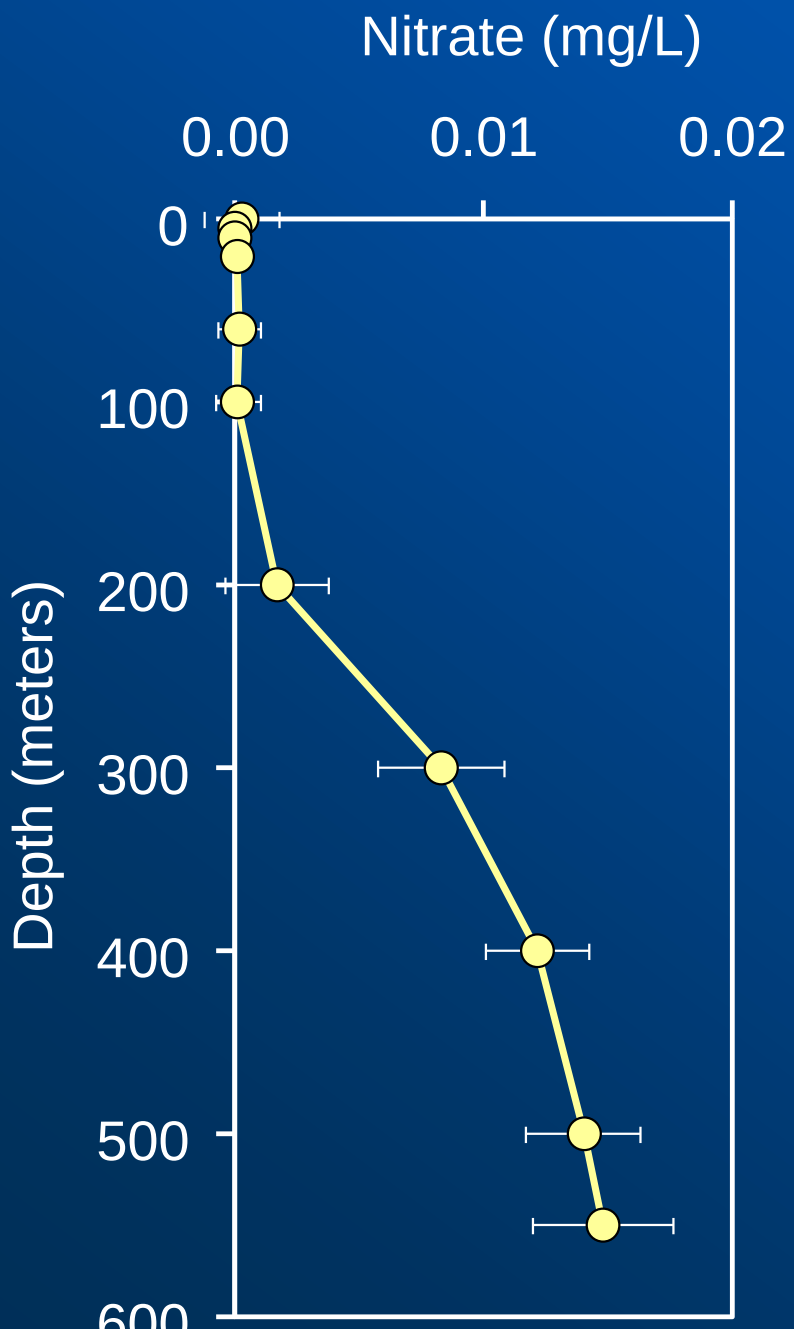
- Surface Area 53.4 km^2
- Volume 19 km^3
- Closed Basin, small watershed
- Elevation 1882 m
- Max depth 592 m, mean depth 350 m

Crater Lake is the centerpiece of a national park, and is known for its exceptional clarity



Source: S. Girdner, Crater Lake National Park

Importance of deep ventilation to nutrient cycling and primary productivity



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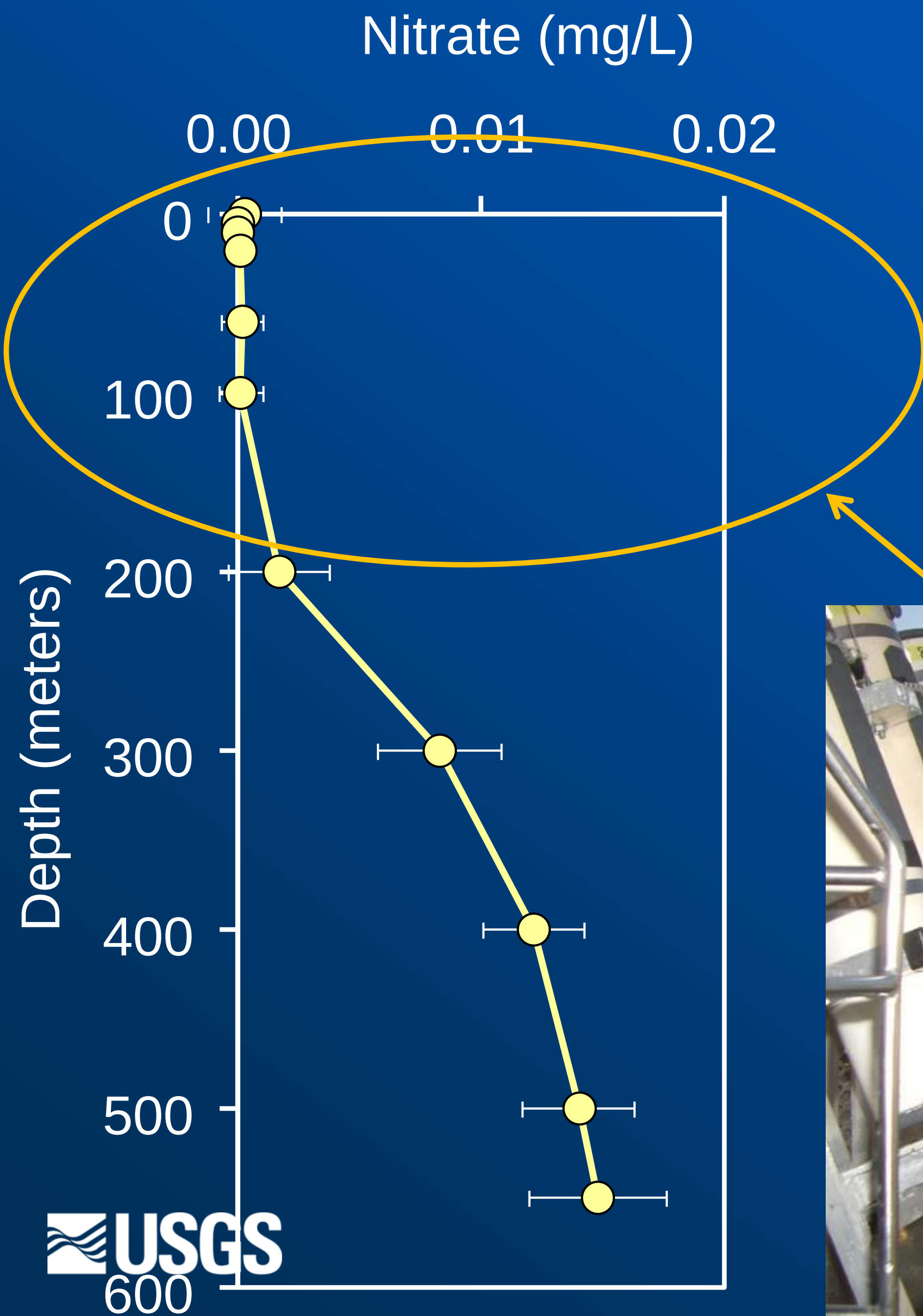
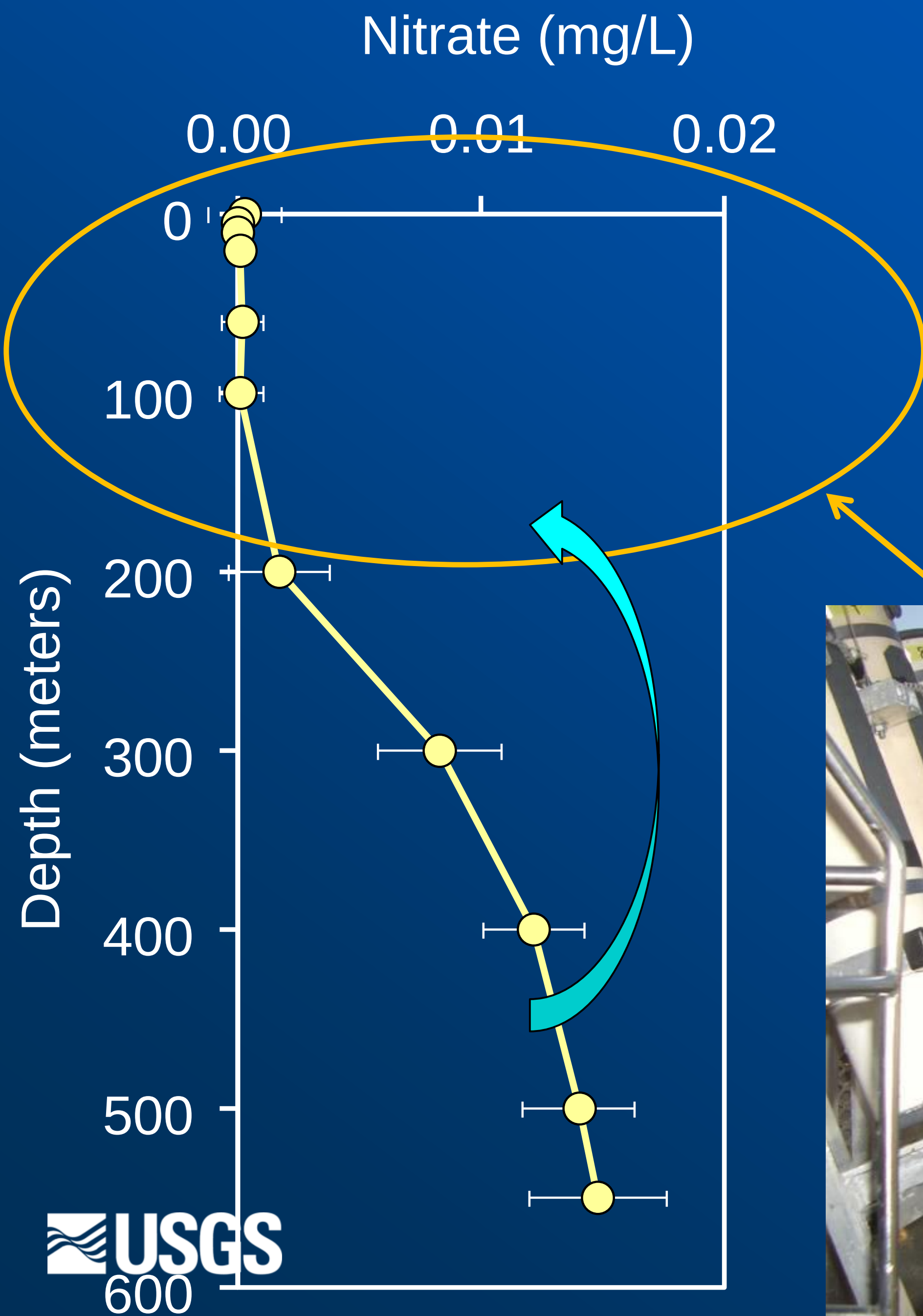


Surface concentrations of nitrate are very low and rapidly assimilated

Source: S. Girdner, Crater Lake National Park

Importance of deep ventilation to nutrient cycling and primary productivity



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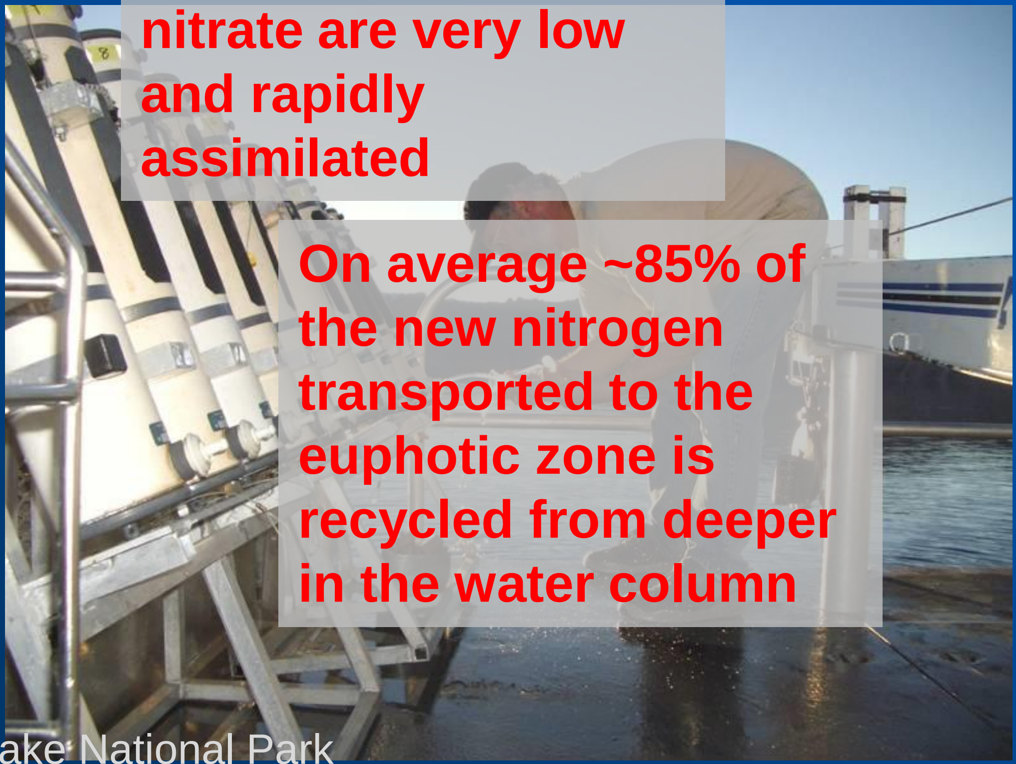
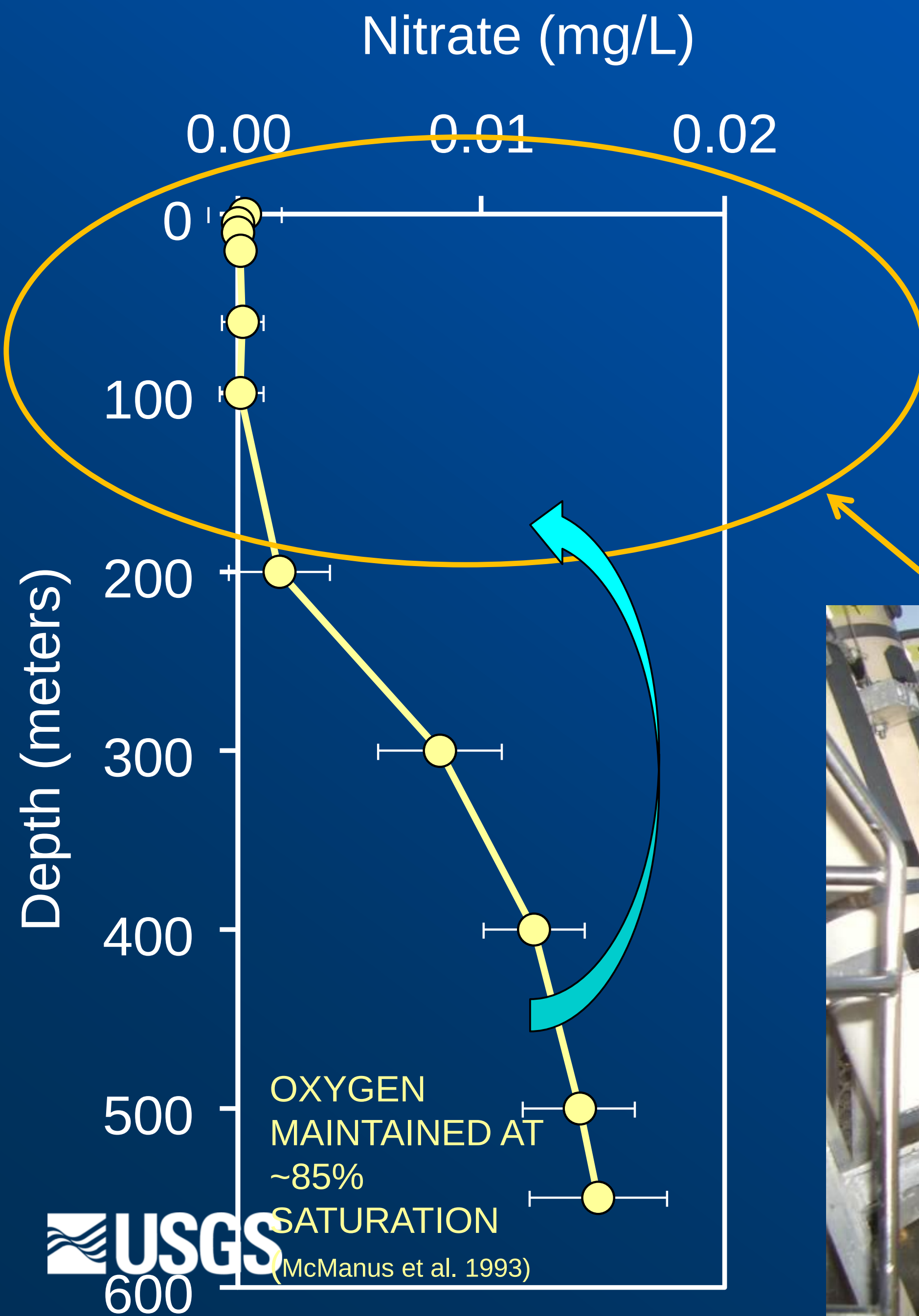


On average ~85% of the new nitrogen transported to the euphotic zone is recycled from deeper in the water column

Source: S. Girdner, Crater Lake National Park

Importance of deep ventilation to nutrient cycling and primary productivity



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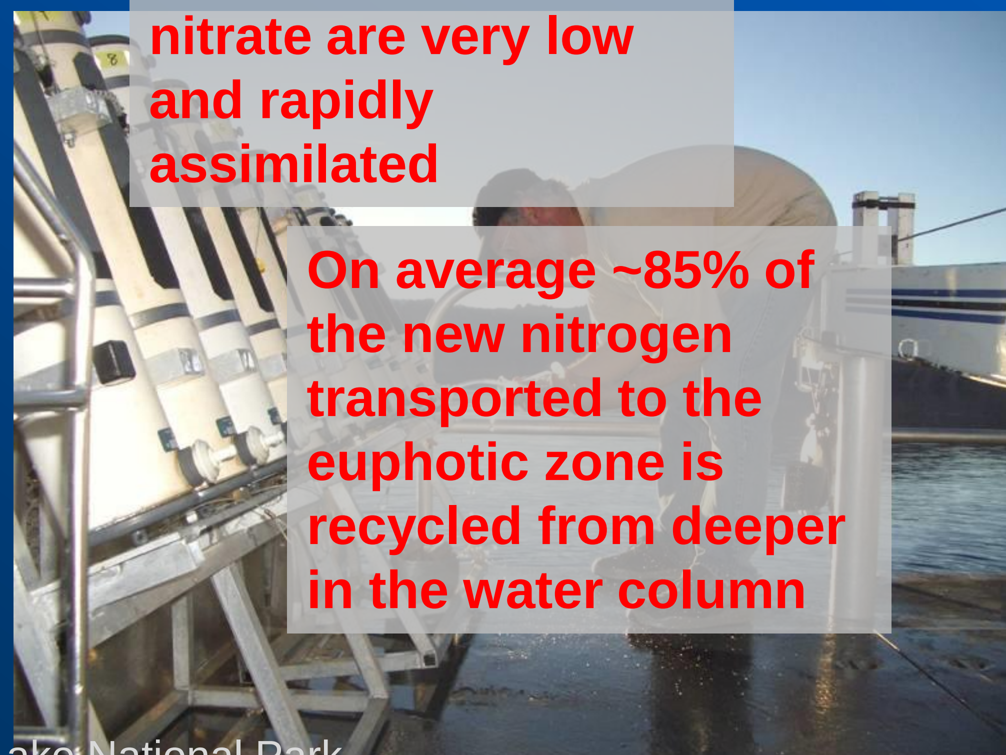

On average ~85% of the new nitrogen transported to the euphotic zone is recycled from deeper in the water column

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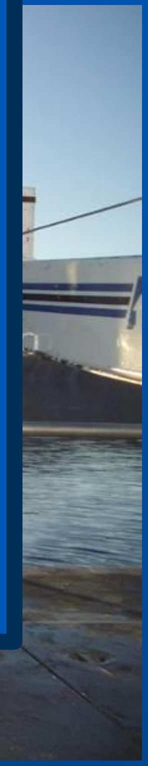
Nitrate (mg/L)

Depth (meters)

Maintenance of minimal primary production and bottom dissolved oxygen concentrations near saturation requires exchange of water between the surface and the greatest depths in the lake

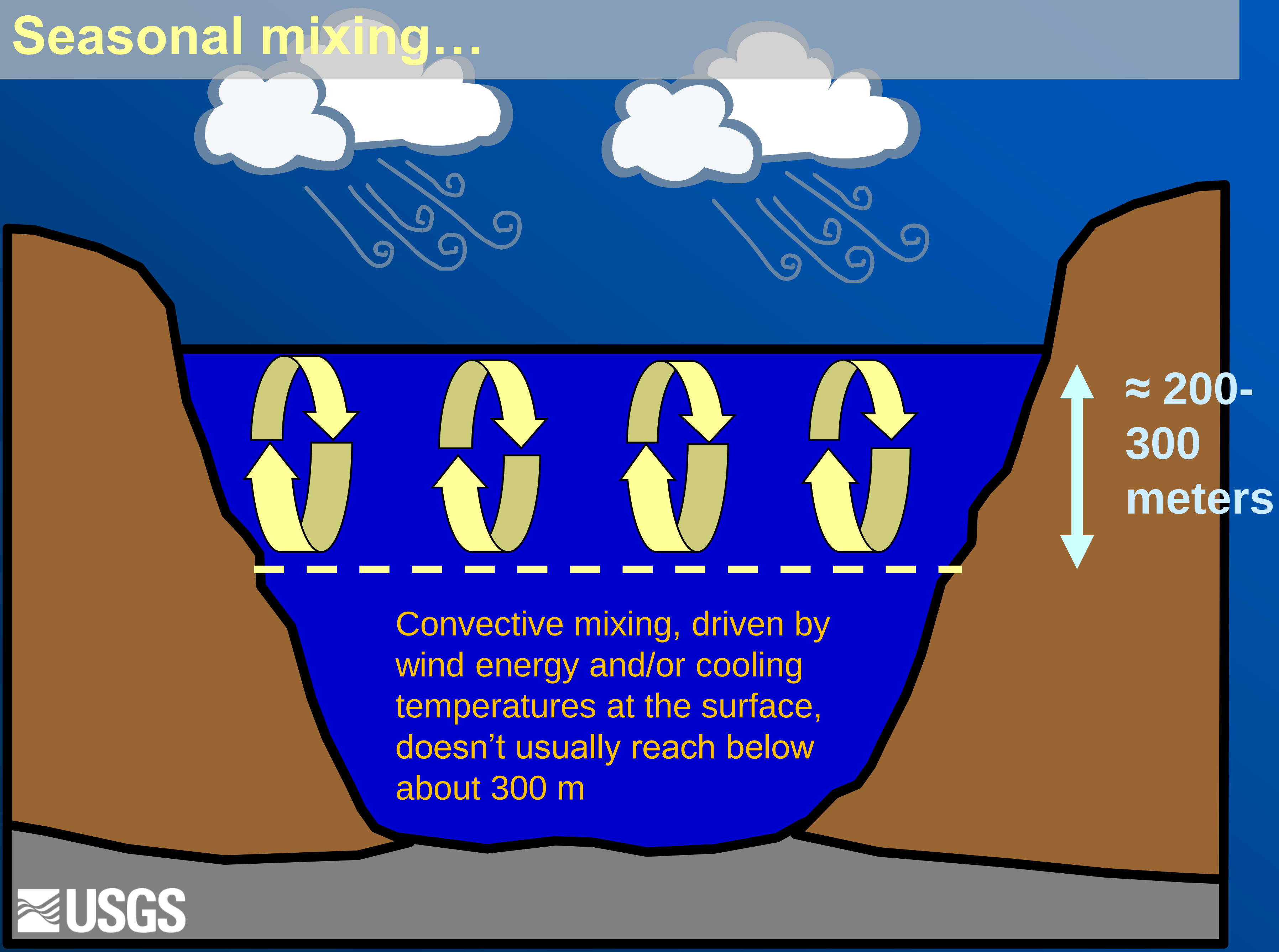


(McManus et al. 1993)

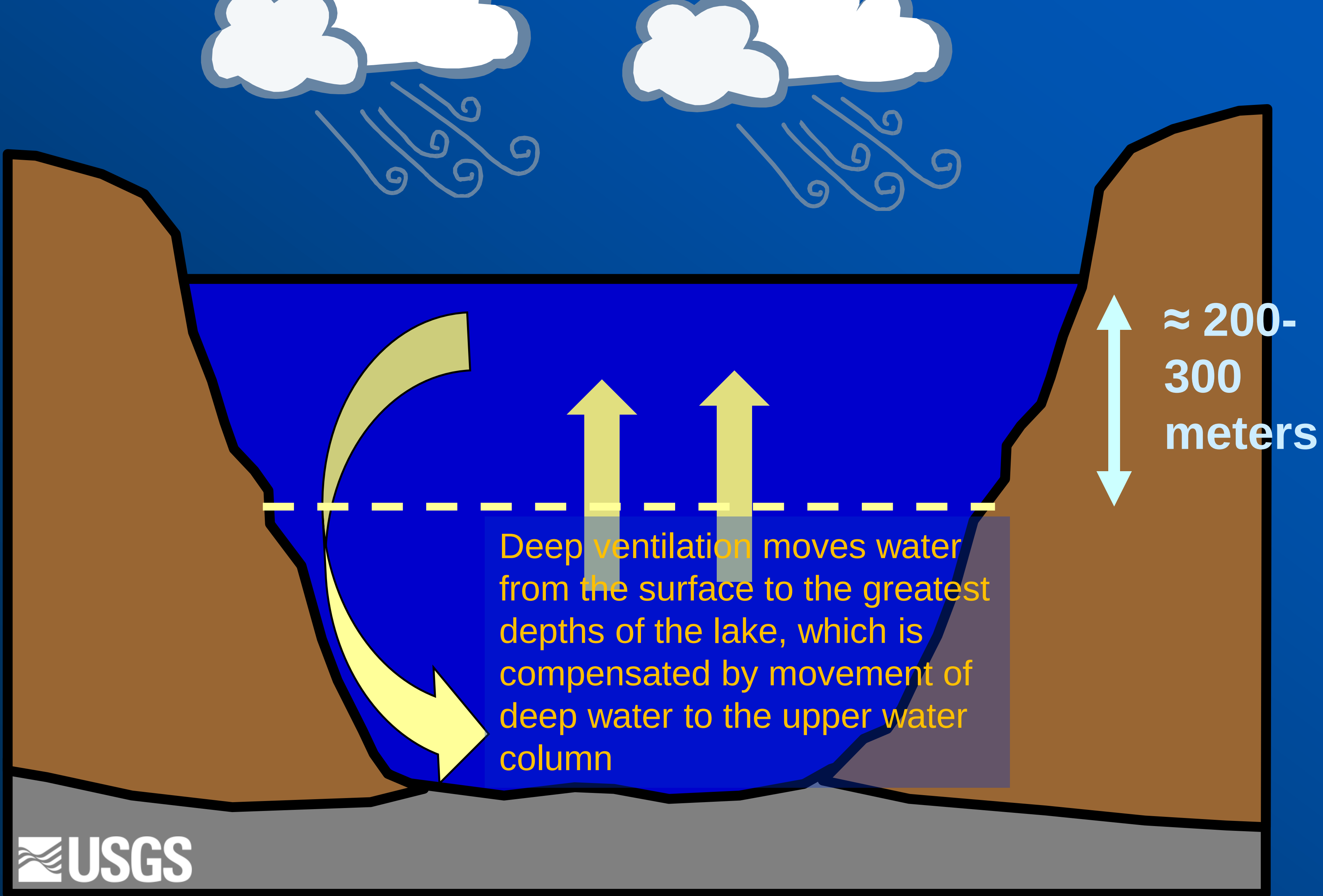
600

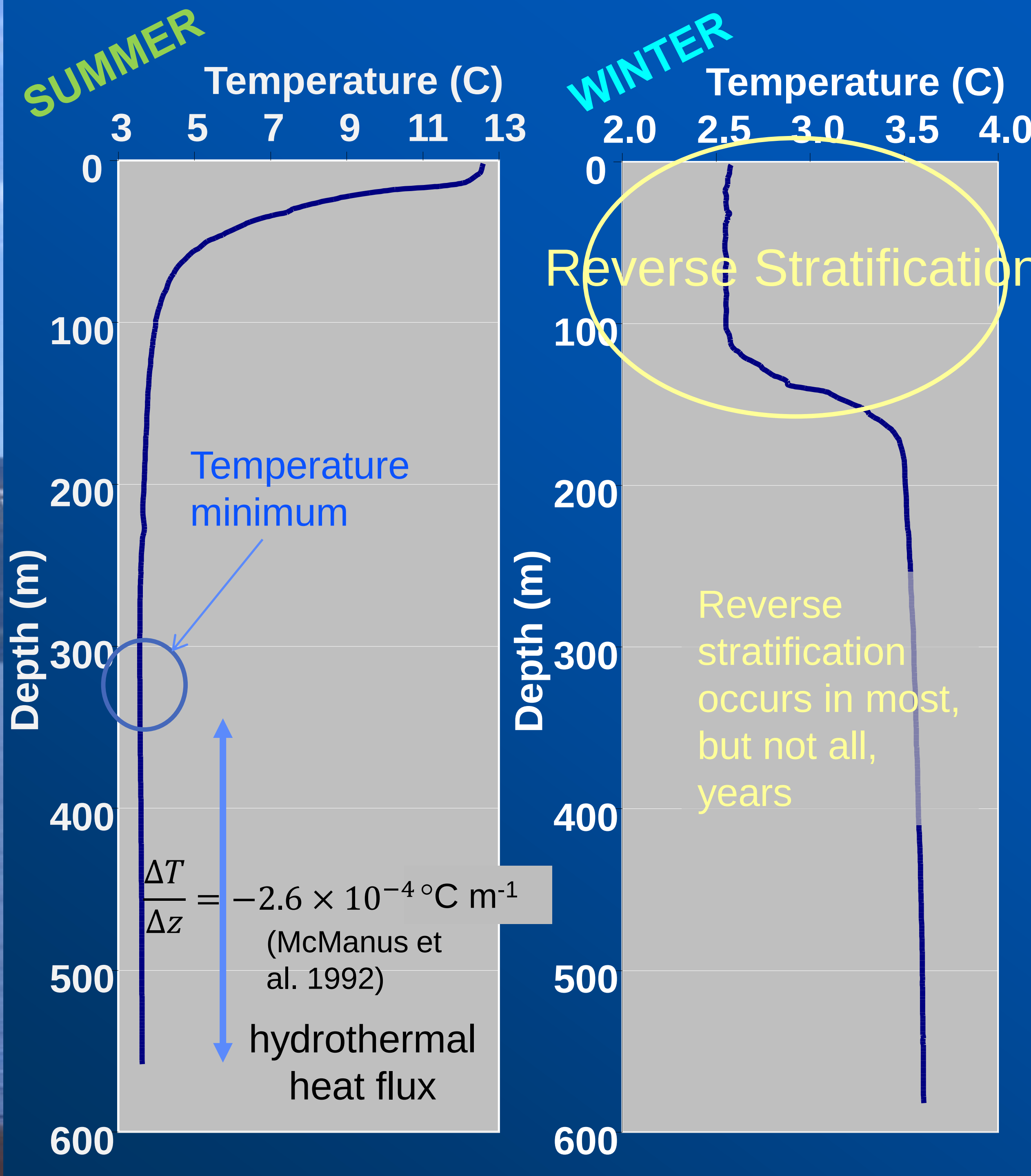
Source: S. Girdner, Crater Lake National Park

Seasonal mixing…



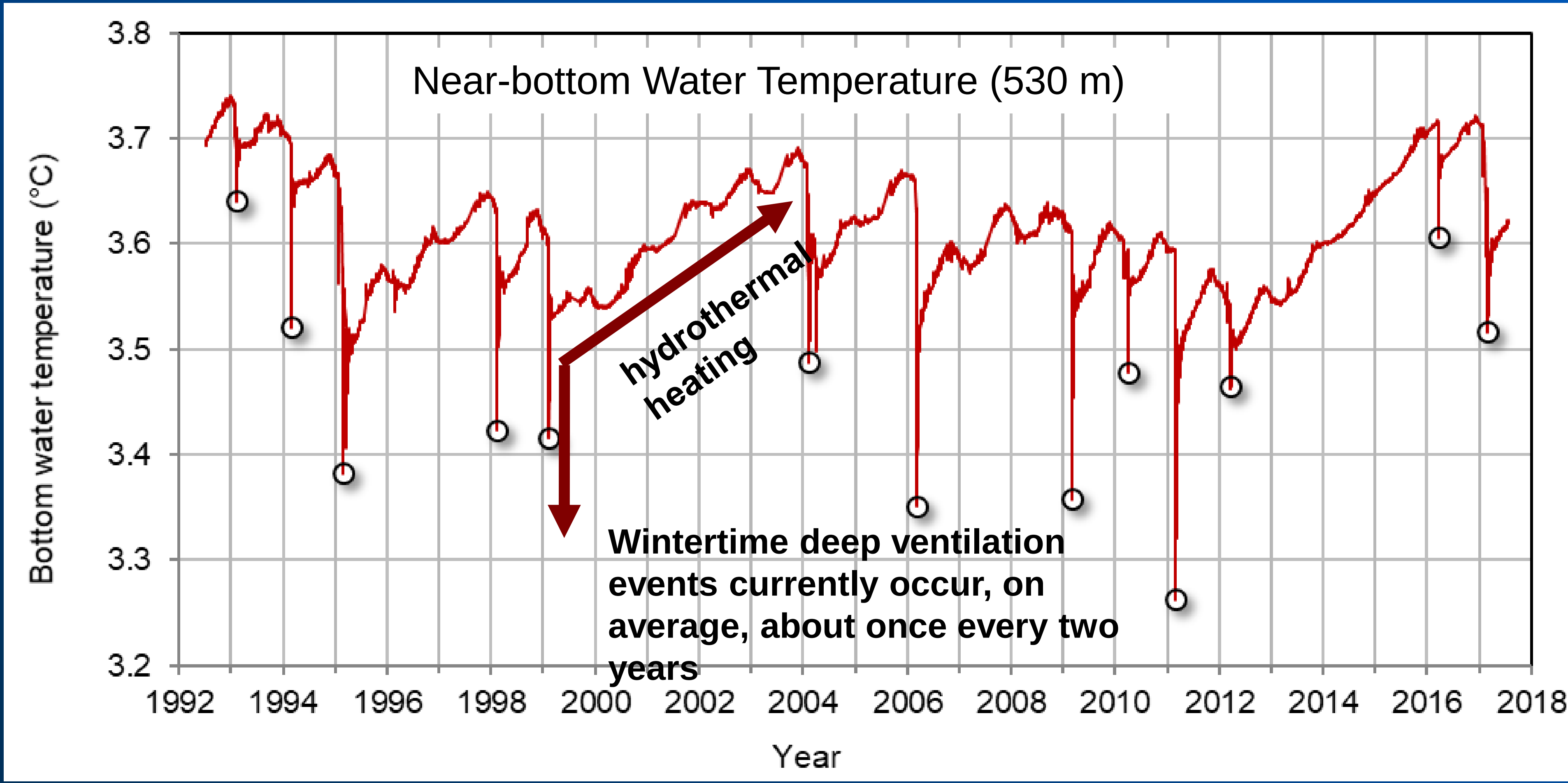
Wintertime deep ventilation...





SUMMER
Temperature (C)
3 5 7 9 11 13
0
100
200
300
400
500
600
Depth (m)
Temperature minimum
$\frac{\Delta T}{\Delta z} = -2.6 \times 10^{-4}$ °C m-1
(McManus et al. 1992)
hydrothermal heat flux
WINTER
Temperature (C)
2.0 2.5 3.0 3.5 4.0
Reverse Stratification
Reverse stratification occurs in most, but not all, years

Deep ventilation is evident in the deep thermistor data as cold spikes



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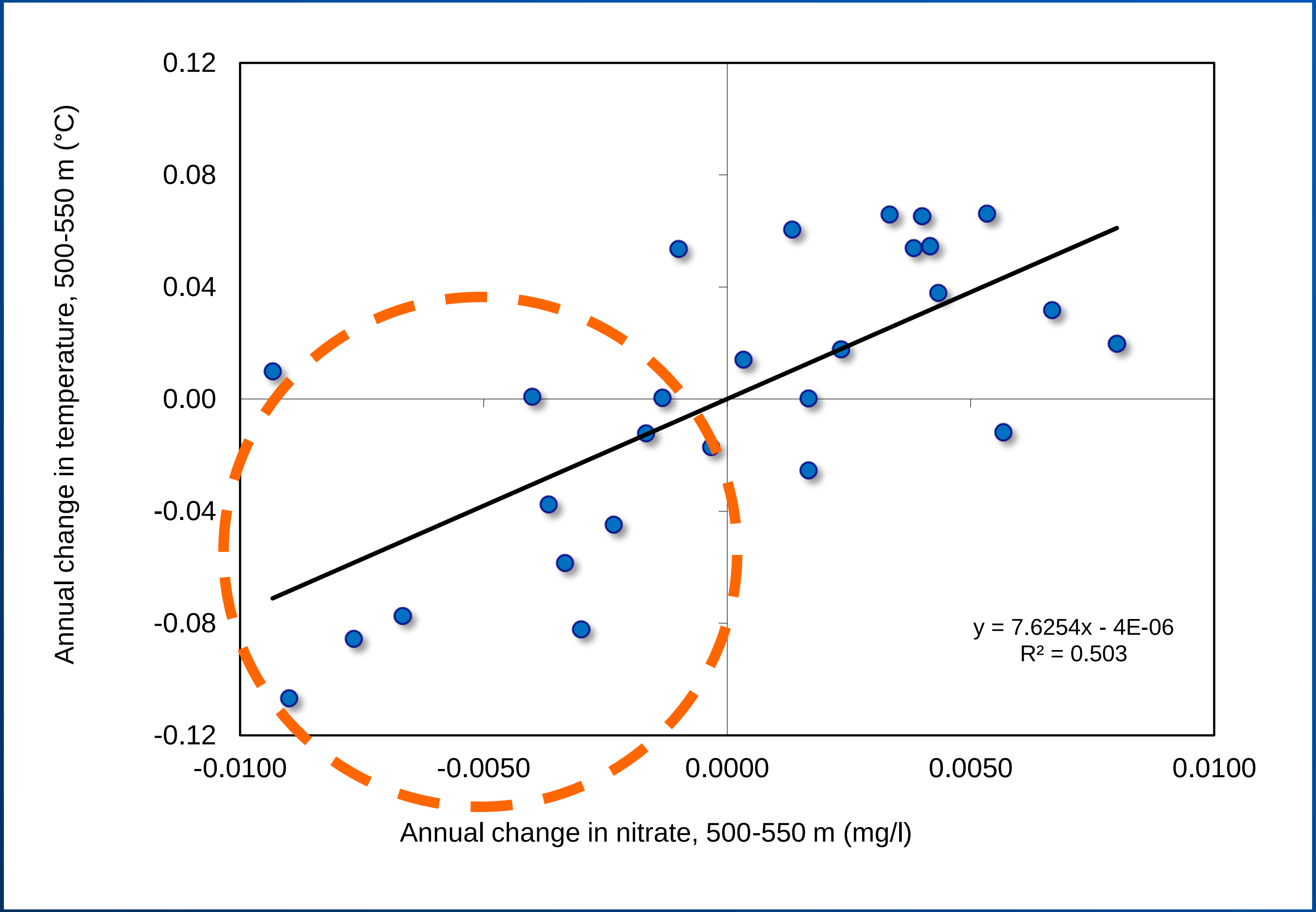
Source: S. Girdner, Crater Lake National Park

Deep ventilation is evident in deep nutrient data as a decrease in nitrate concentration



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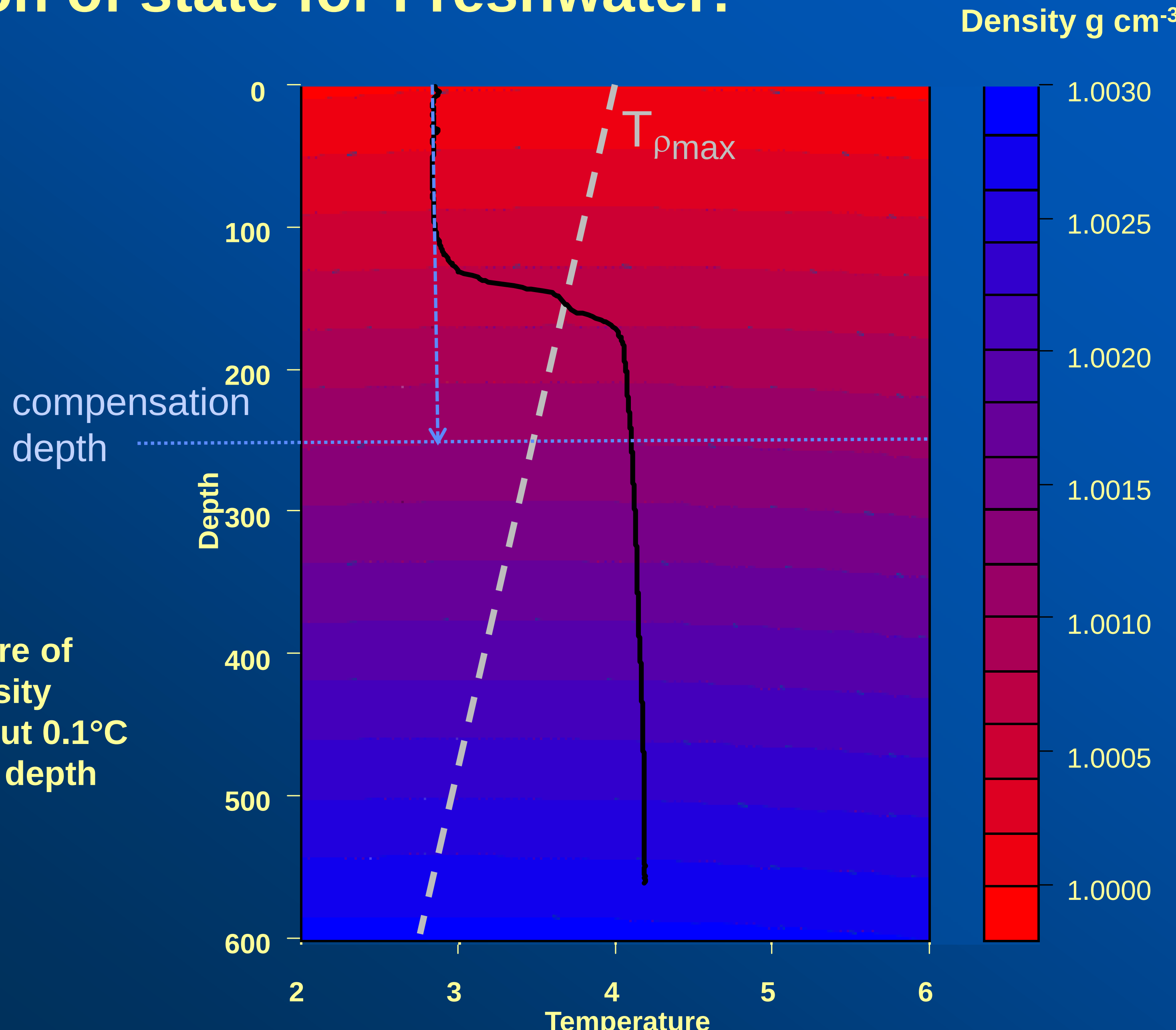
Source: S. Girdner, Crater Lake National Park

Equation of state for Freshwater:



The temperature of maximum density decreases about 0.1°C for every 50 m depth

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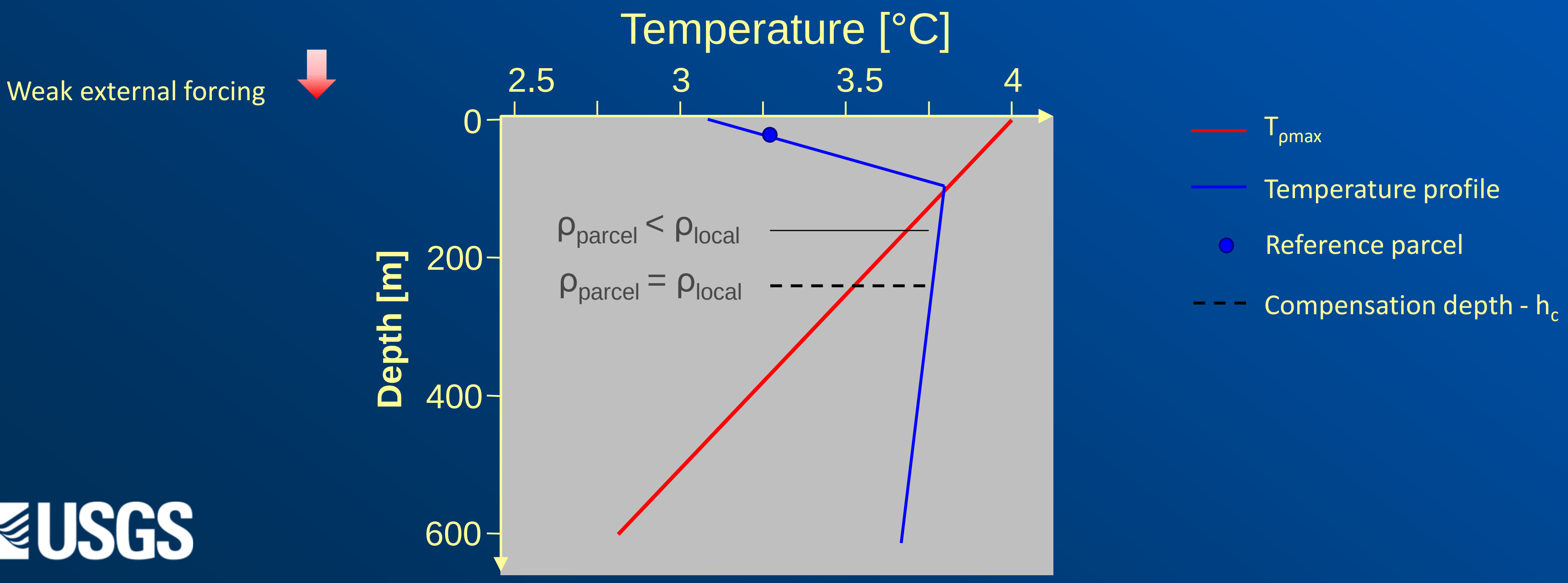
Deep ventilation in Crater Lake: the physical mechanism

- Requires reverse stratification
- Density depends on temperature and pressure (Chen and Millero, 1976)
- Temperature of maximum density decreases with depth from ~4°C at the surface to ~2.8°C at 600 m
- In the presence of weak external forcing, positive restoring buoyancy returns displaced surface water to the surface



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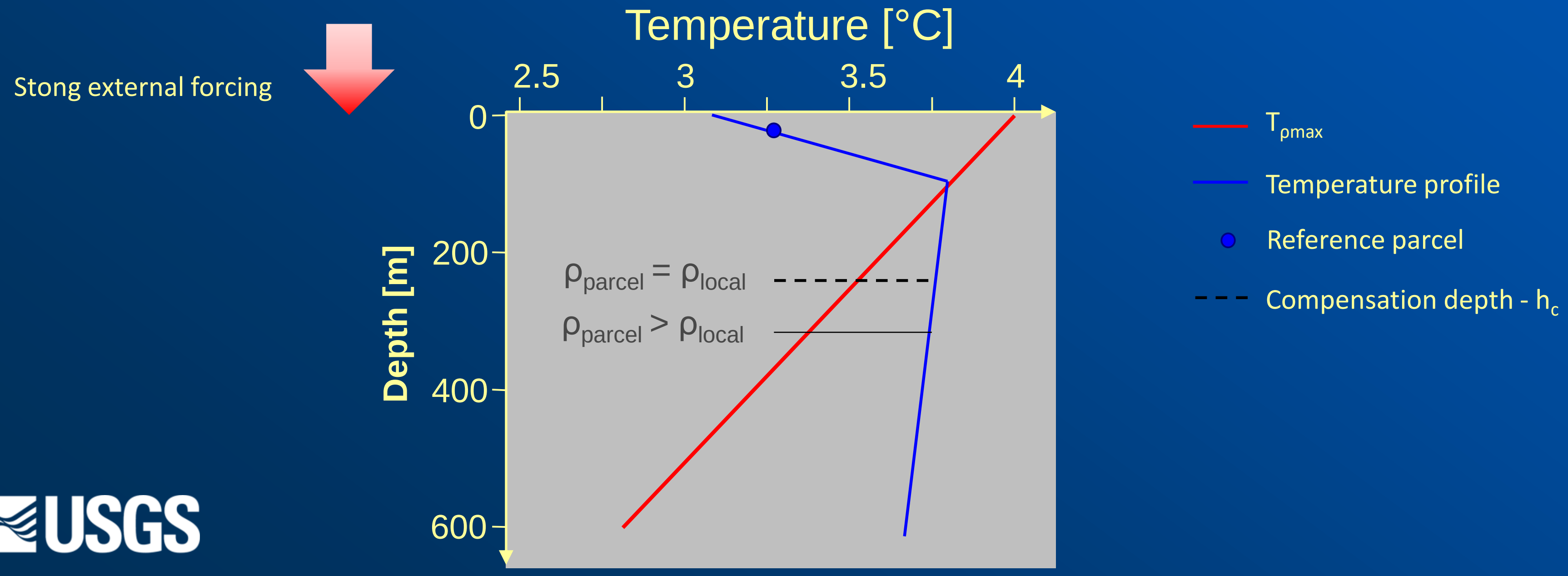
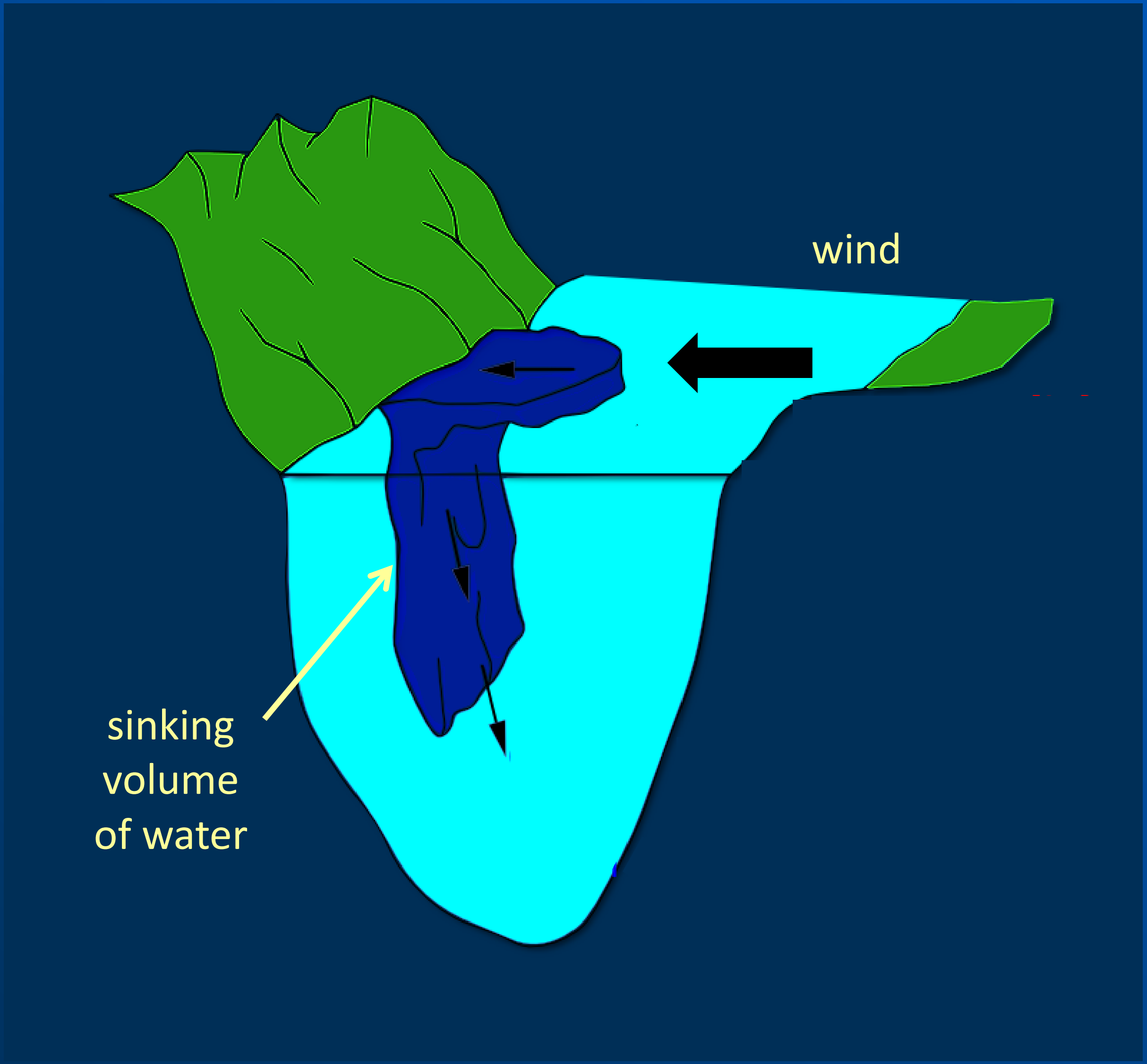
Deep ventilation in Crater Lake: the physical mechanism

- **Requires reverse stratification**
- **Density depends on temperature and pressure (Chen and Millero, 1976)**
- **Temperature of maximum density decreases with depth from ~4°C at the surface to ~2.8°C at 600 m**
- **In the presence of strong external forcing, surface water can be forced to a depth at which there is no longer a positive restoring buoyancy**
- **Triggered by thermobaric instability (Crawford and Collier, 2007)**



Deep ventilation at the shoreline of Crater Lake

Deep ventilation as a result of thermobaric instability is a 3-dimensional, basin-scale process



Given that:

- Deep ventilation is driven by thermobaric instability, requiring reverse stratification, and
- Reverse stratification does not currently happen every year,

The question arises: Will the frequency of deep ventilation change in a future climate?

We investigate this question with 1DDV: A simplified 1D model developed to represent the phenomenon of deep ventilation, originally for Lake Baikal (Piccolroaz and Toffolon, 2013).

1DDV requires lake surface temperature and wind as boundary conditions.

The lumped model *air2water* was used to determine lake surface temperature from air temperature alone (Toffolon, et al. 2014).

The combination is well-suited to predicting long-term dynamics (i.e. climate change scenarios) because it accurately simplifies a basin-scale phenomenon, and requires few input data.

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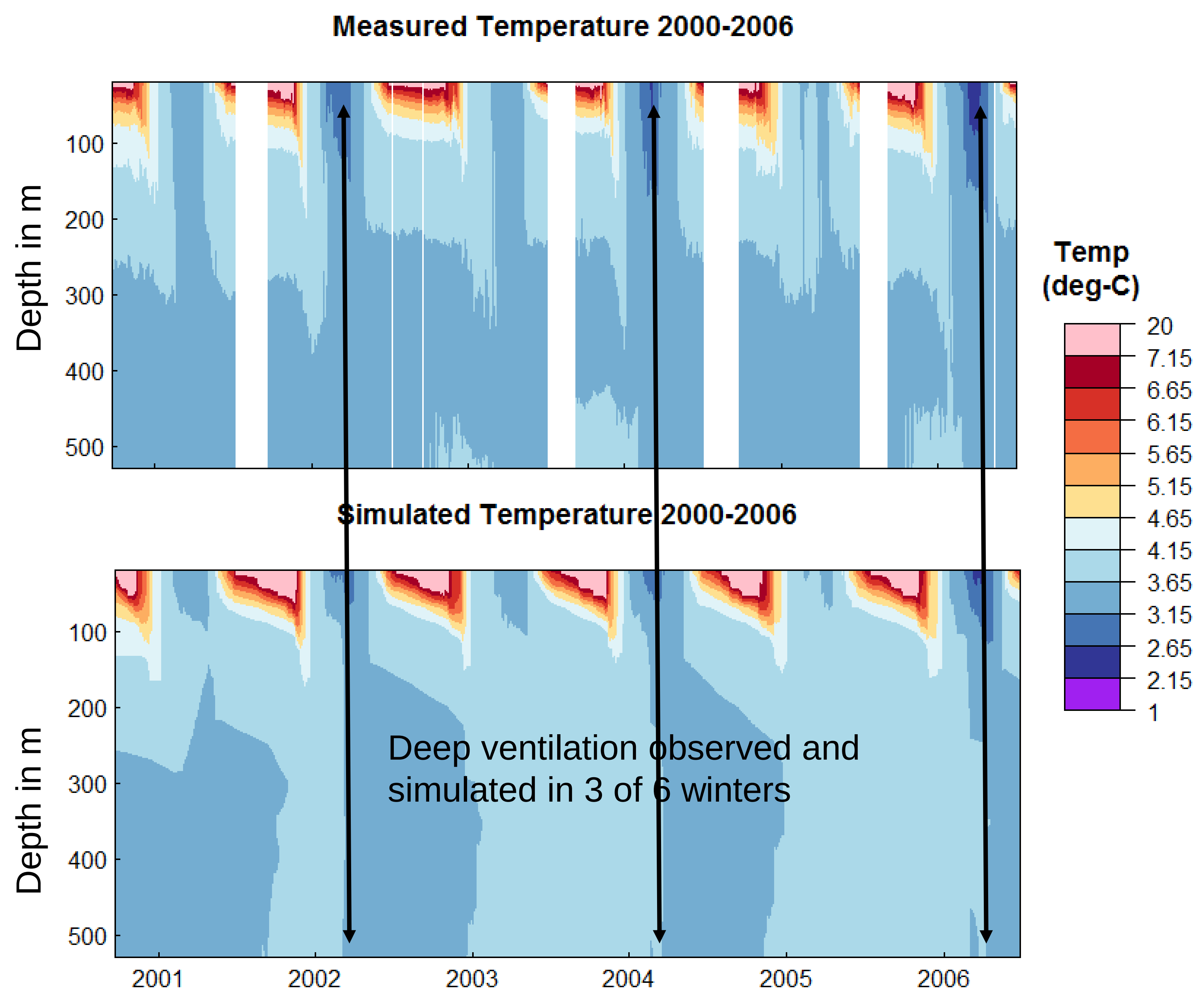
1DDV Calibration



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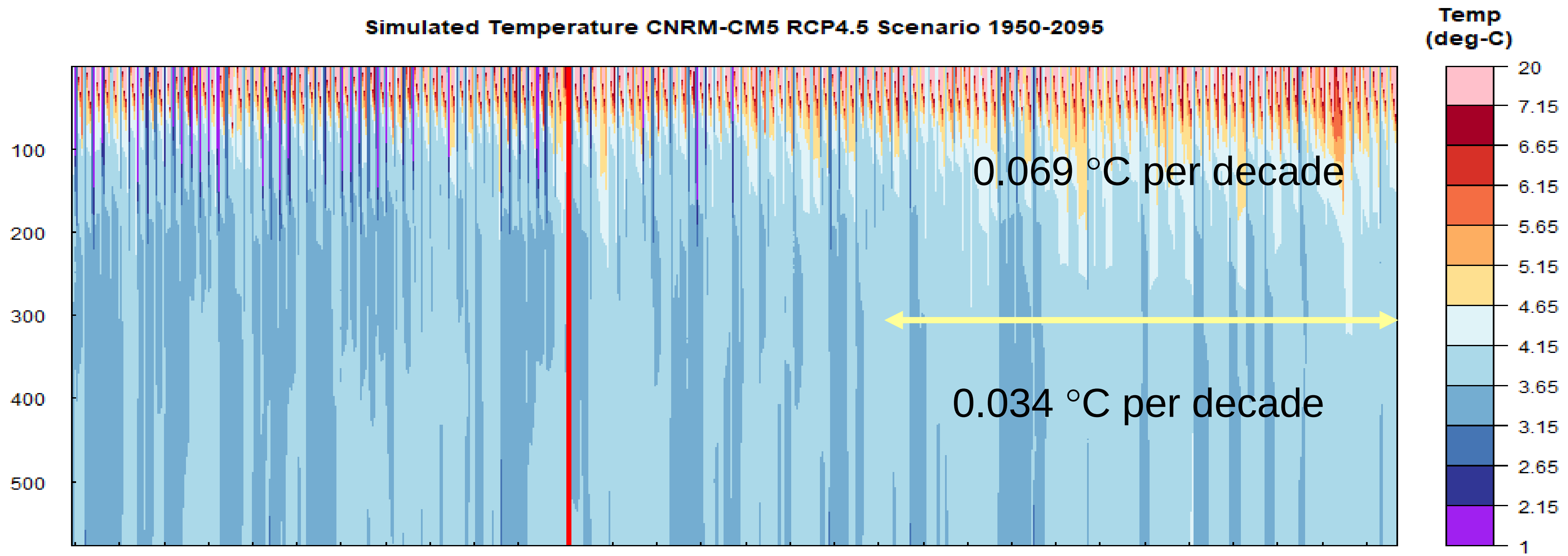
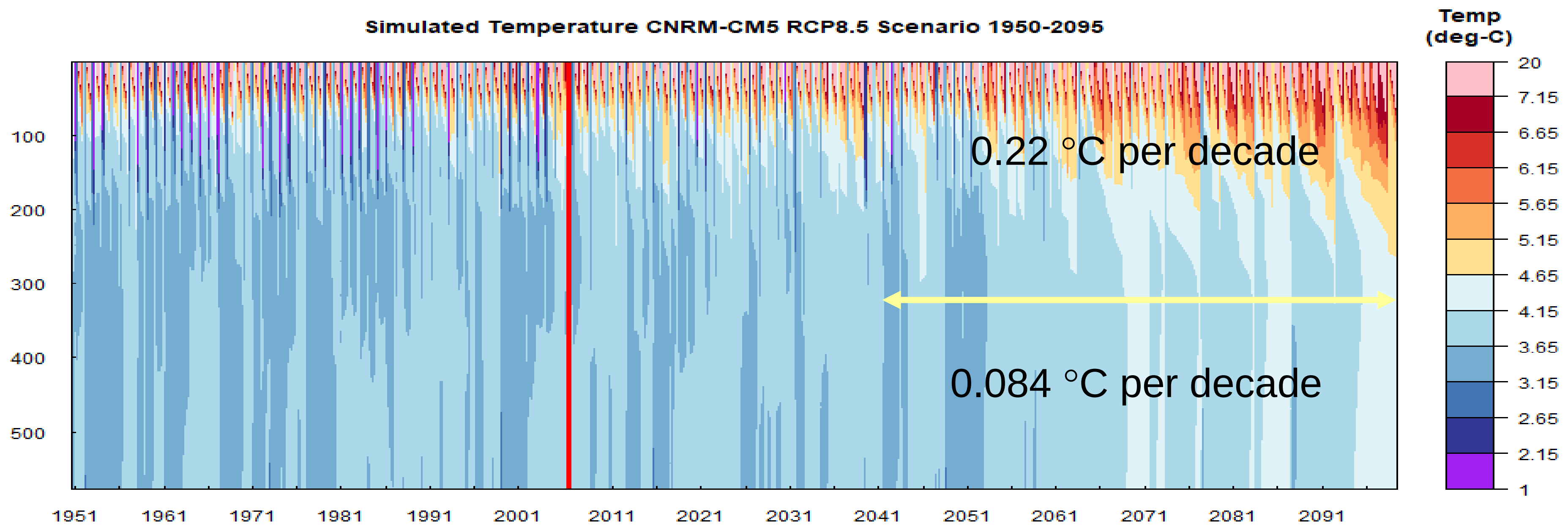
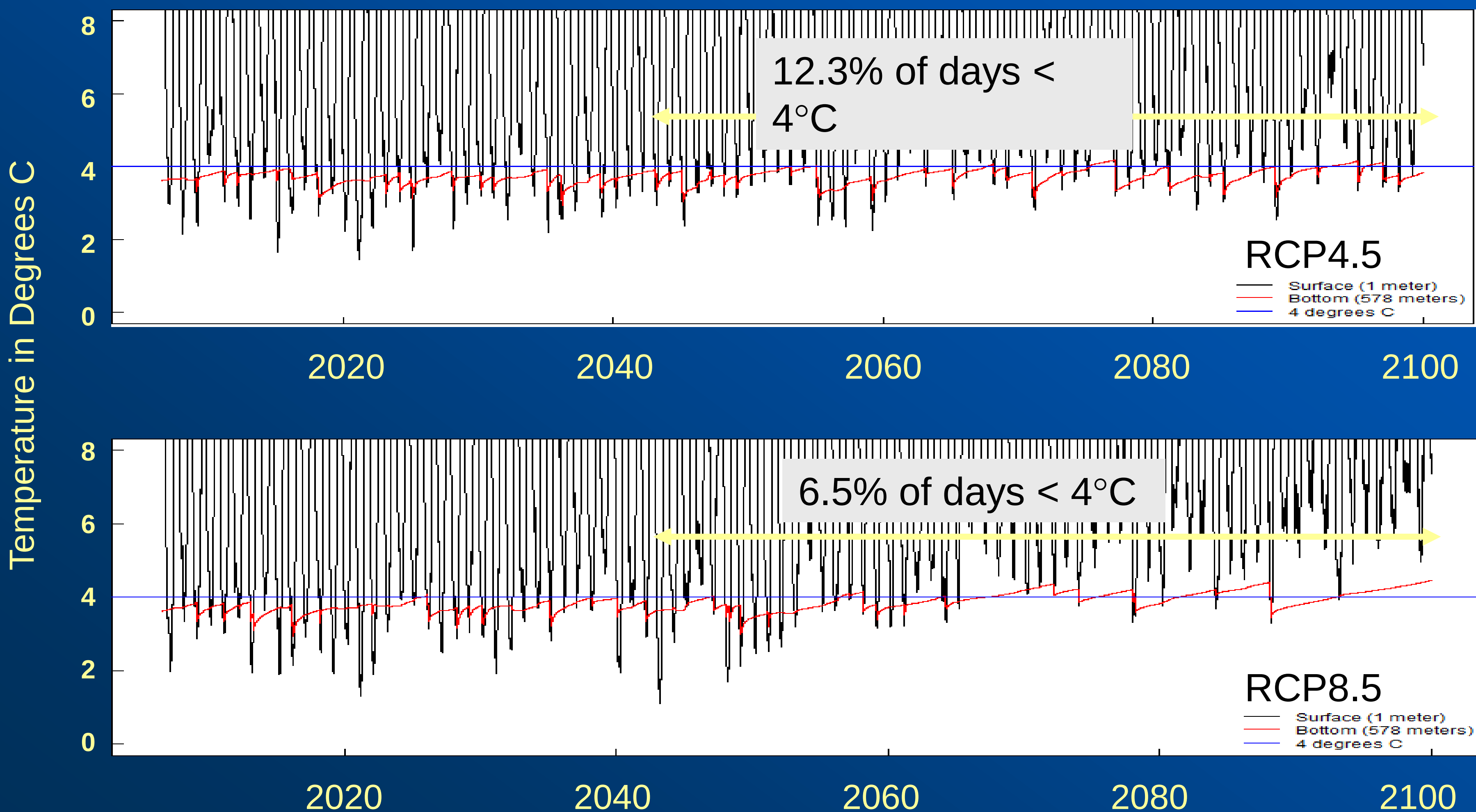


Simulated Temperature CNRM-CM5 RCP4.5 Scenario 1950-2095
Temp (deg-C)
20
7.15
6.65
6.15
5.65
5.15
4.65
4.15
3.65
3.15
2.65
2.15
1
100
200
300
400
500
0.069 °C per decade
0.034 °C per decade



Simulated Temperature CNRM-CM5 RCP8.5 Scenario 1950-2095
Temp (deg-C)
20
7.15
6.65
6.15
5.65
5.15
4.65
4.15
3.65
3.15
2.65
2.15
1
100
200
300
400
500
0.22 °C per decade
0.084 °C per decade
1951
1961
1971
1981
1991
2001
2011
2021
2031
2041
2051
2061
2071
2081
2091

Surface and Bottom Temperature, Future Conditions, CNRM-CM5



35.6% of days < 4°C during baseline period 1951-2005

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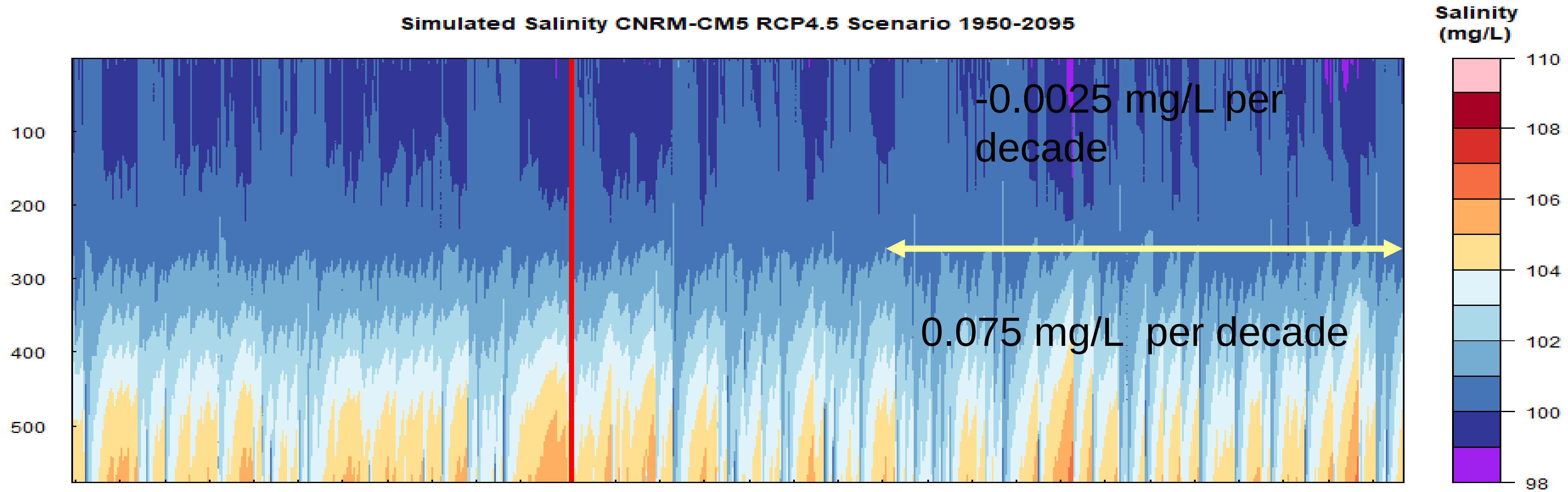
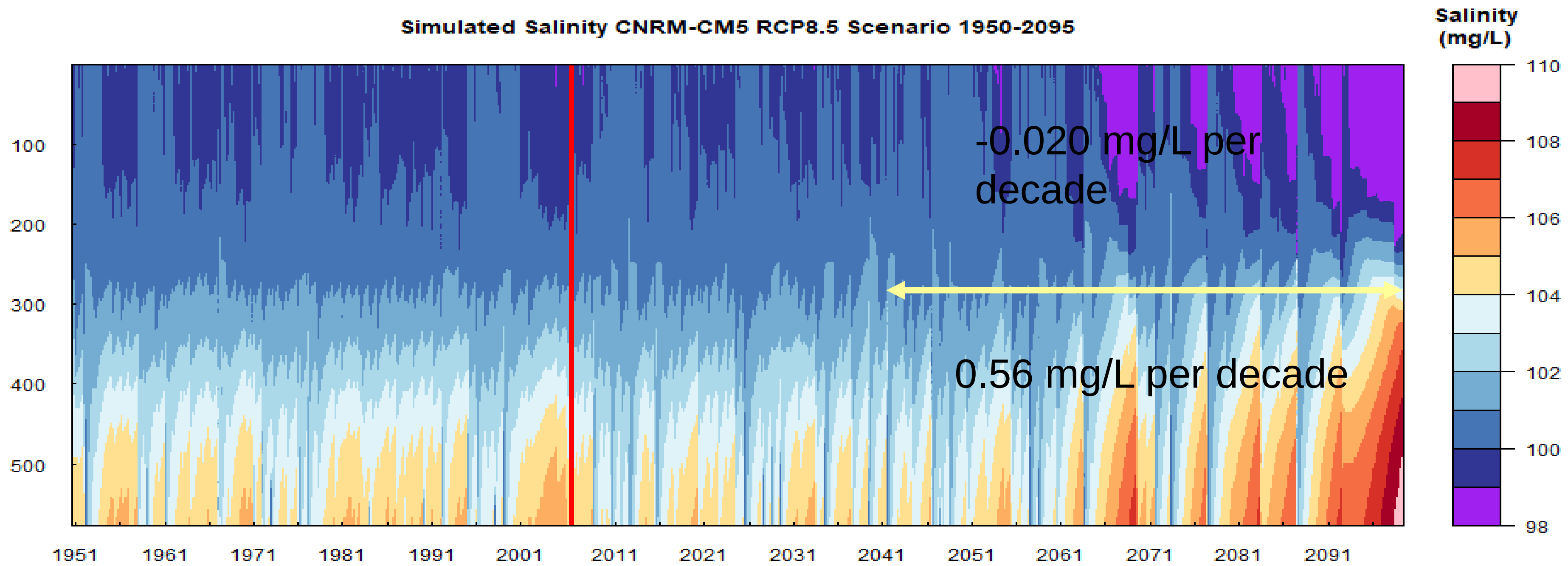
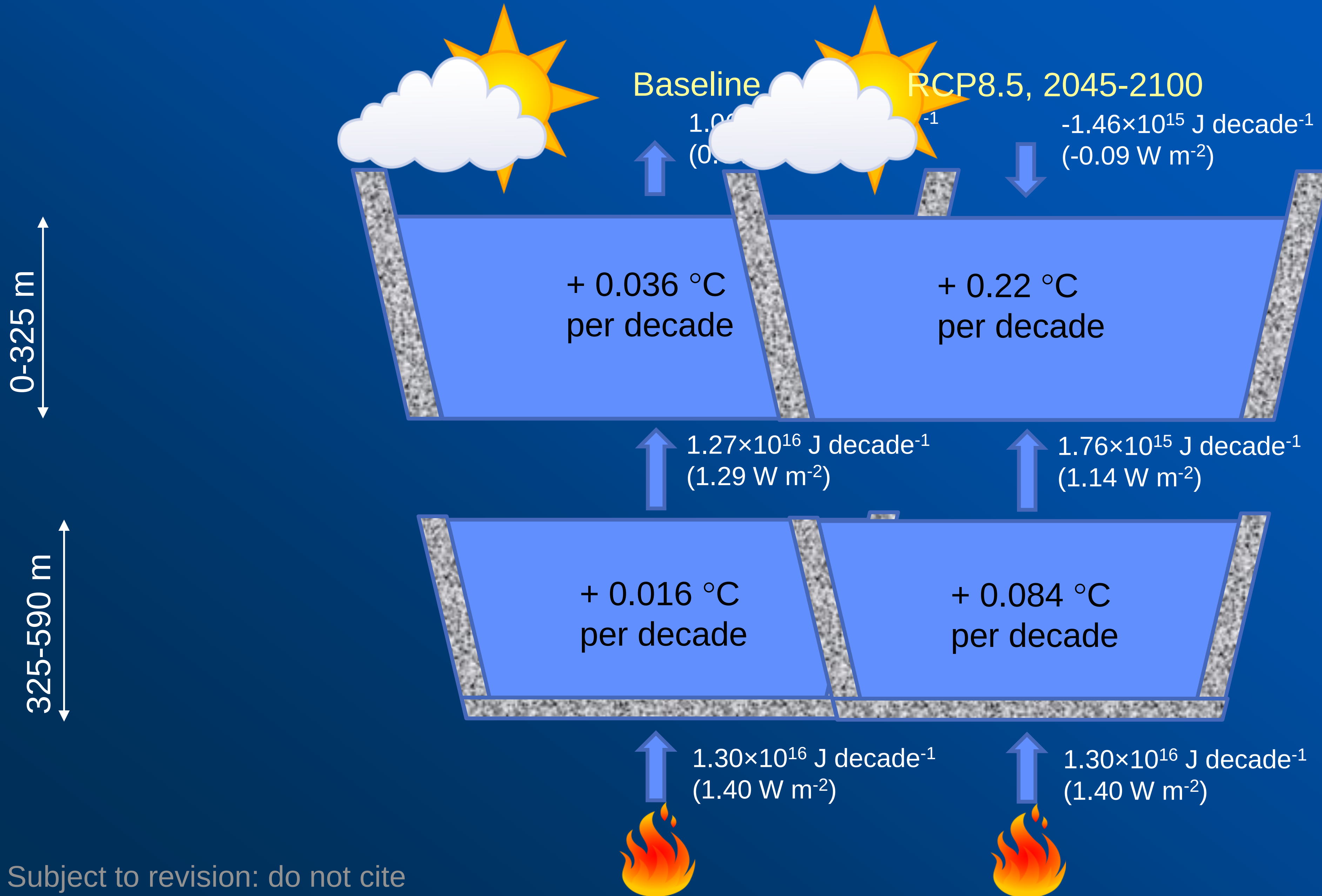

Simulated Salinity CNRM-CM5 RCP4.5 Scenario 1950-2095
Salinity (mg/L)
110
108
106
104
102
100
98
100
200
300
400
500
-0.0025 mg/L per decade
0.075 mg/L per decade


Simulated Salinity CNRM-CM5 RCP8.5 Scenario 1950-2095
Salinity (mg/L)
110
108
106
104
102
100
98
100
200
300
400
500
-0.020 mg/L per decade
0.56 mg/L per decade
1951
1961
1971
1981
1991
2001
2011
2021
2031
2041
2051
2061
2071
2081
2091

CNRM Heat Balance, 2-layer Crater Lake



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Conclusions

- All climate scenarios predict increased water temperature throughout the water column, and a reduced frequency of reverse stratification in winter, particularly in the latter part of the 21st century

- Reduced frequency of deep ventilation would lead to reduced nitrate inputs to upper water column and potentially reduced primary productivity- but probably not reduced clarity

- Reduced frequency of deep ventilation would result in depletion of near-bottom dissolved oxygen over time

- Determination of the magnitude and rate of progression of these changes requires coupling to a biological model

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Conclusions, continued

- What Crater Lake says about the response of deep lakes with significant hydrothermal fluxes to climate change:
  - The change in hypolimnion temperature in lakes that are solidly dimictic and reliably reverse stratify in winter is likely to be muted; in contrast,
  - Deep lakes that depend on thermobaric instability for deep ventilation are vulnerable if they are already marginal for wintertime reverse stratification, and
  - The hypolimnion temperature in lakes with large hydrothermal fluxes could increase relatively rapidly once deep ventilation becomes rare and the hydrothermal heat is not vented to the atmosphere

Acknowledgments

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