Modeling the Oceanic Surface Saturation of CFC-11, CFC-12, and SF6

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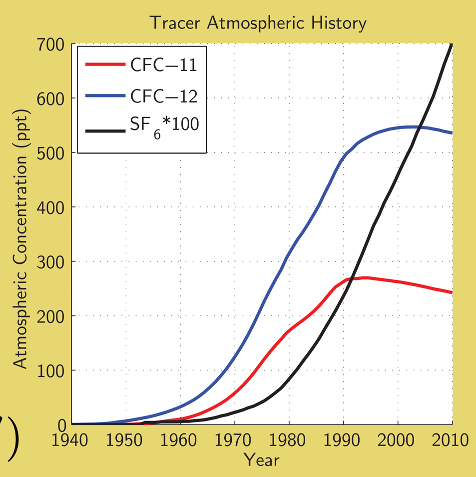
Motivation: Why is saturation important?

CFCs, SF6 as tracers of circulation

- Known atmospheric mixing ratio history
- Sole oceanic source: air-sea gas exchange
- Inert in the oceanic interior
- Present in measurable concentrations



Application: Transit Time Distributions[1]

$$C^{\mathcal{I}}(\vec{x},t) = \int_S dx' \int_{t_0}^{t} dt' C^S(x',t')\mathcal{G}(\vec{x},t|x',t')$$

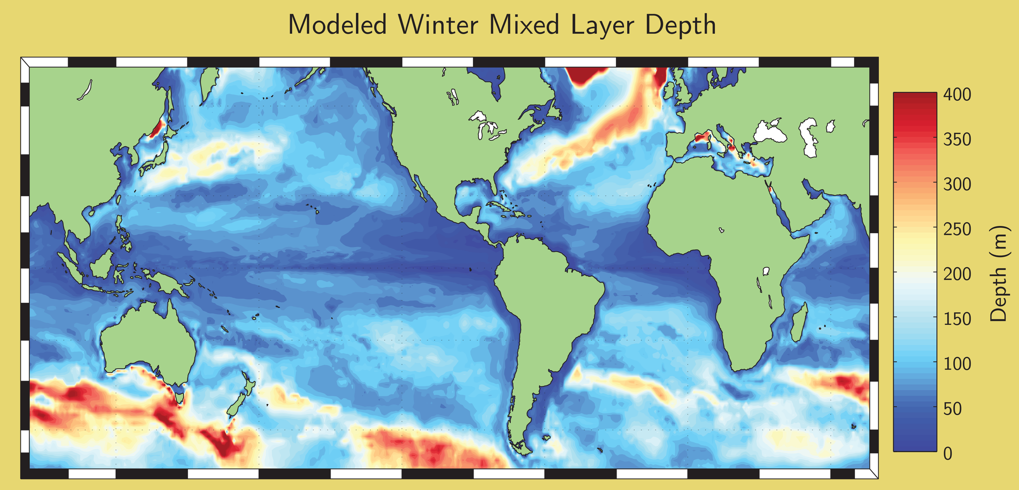
- Infer Green's function for oceanic transport operator $\mathcal{G}(\vec{x},t)$
- Can estimate mean ventilation ages and anthropogenic carbon[2]
- Oceanic interior concentrations can be measured accurately $C^{\mathcal{I}}(\vec{x},t)$
- Disequilibrium in boundary condition can cause errors $C^S(\vec{x},t)$

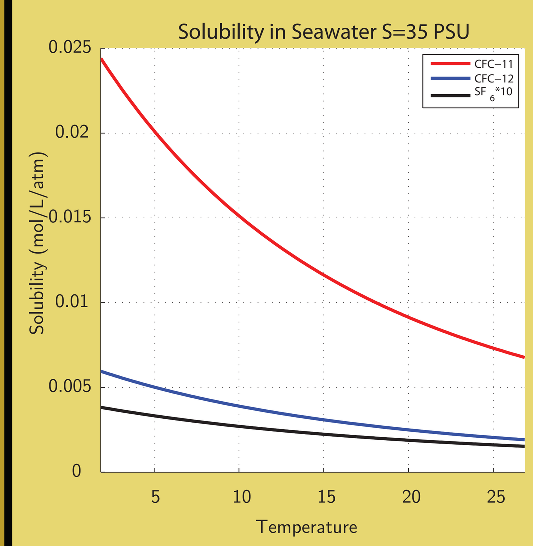
$$\text{Percent Saturation} = 100 \times C_{meas}/\left(F_{sol}\ \text{pCFC}\right)$$

Model Description

Hallberg Isopycnal Model

- Global, ocean-only, isopycnal coordinate model
- 49 layers (4 in mixed layer)
- 210 X 360 cells on horizontal grid
- Spunup for 550 years
- Model's surface dynamics match observations reasonably well





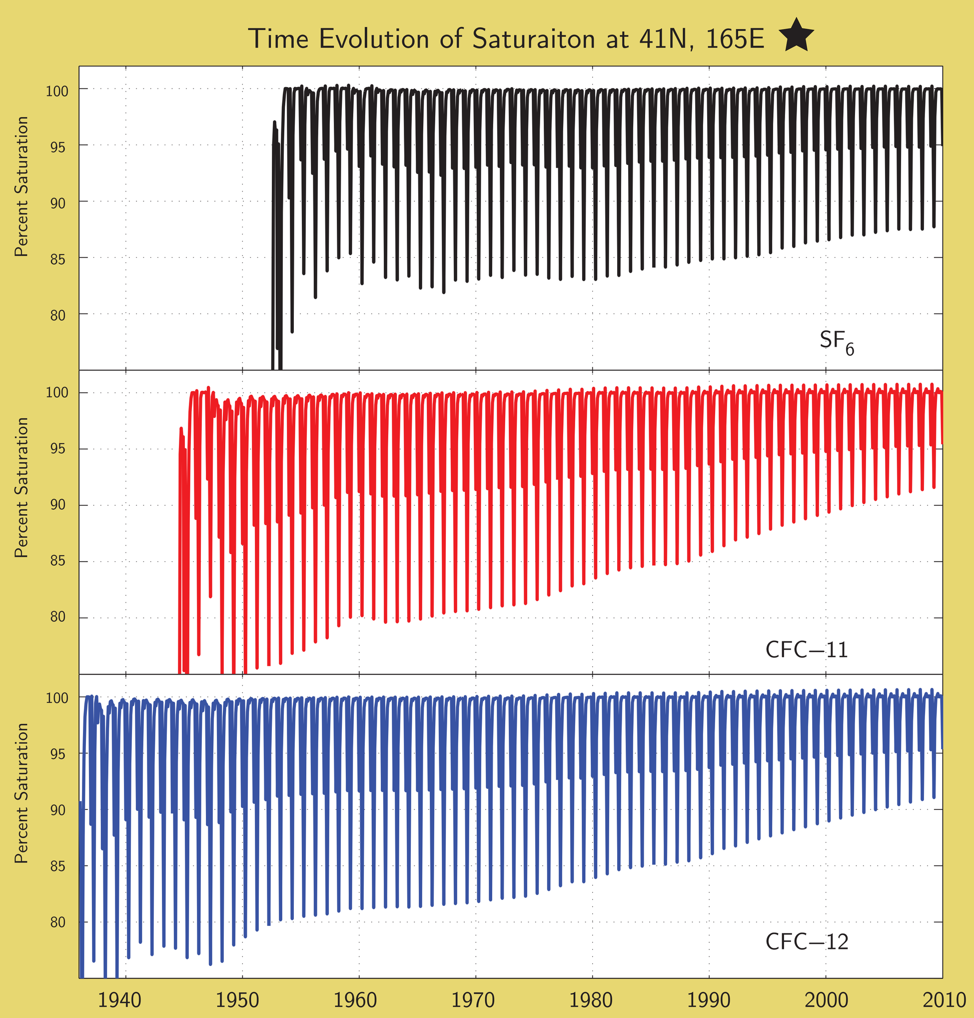
Offtrac

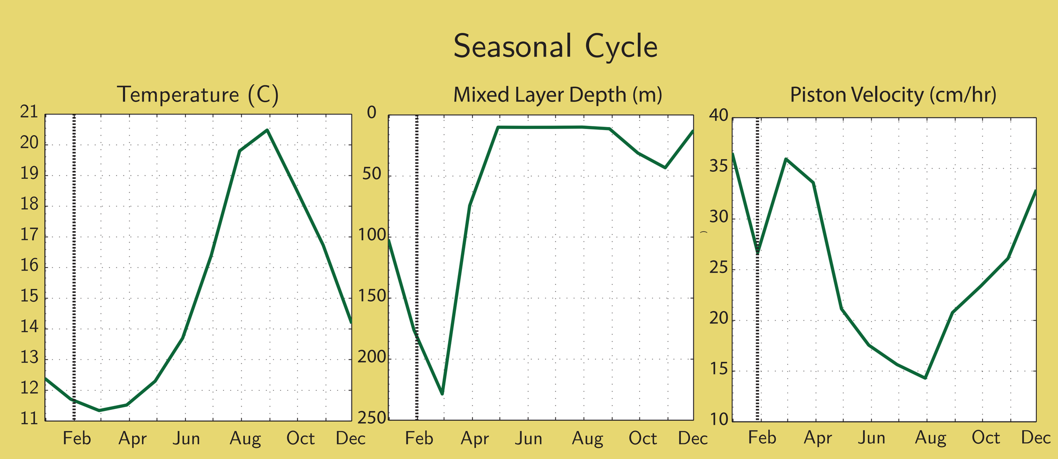
- Tracer advection/diffusion model
- Mass transports, T, S from physical model
- Tracer uptake modeled as 1D air-sea gas exchange
- Solubilities F from empirical studies[3,4]
- Piston velocity k_w parameterized as quadratic function of model's wind speed scaled by Schmidt number[5]
- Global average scaled to 15.7 cm/hr[6]

$$\frac{\partial C}{\partial t} = \frac{k_w(U,\mathrm{Sc})}{H}\left(F_{sol}(\theta,S)\mathrm{pCFC} - C\right)$$

Result: Temporal variability

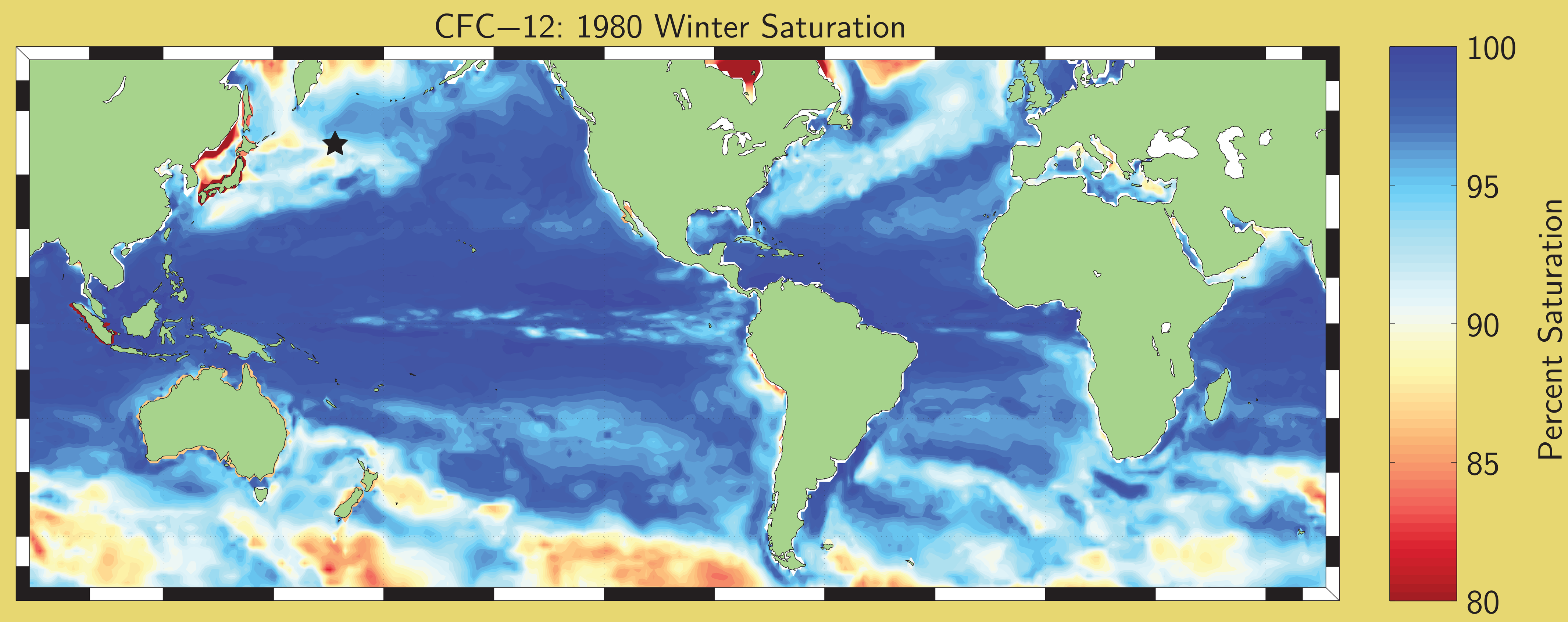
- Disequilibrium decreases with time
- Waters saturated during summer months
- Differences between tracers associated with solubility and atmospheric growth curve
- Present day CFC undersaturations persist despite decrease in atmospheric concentrations





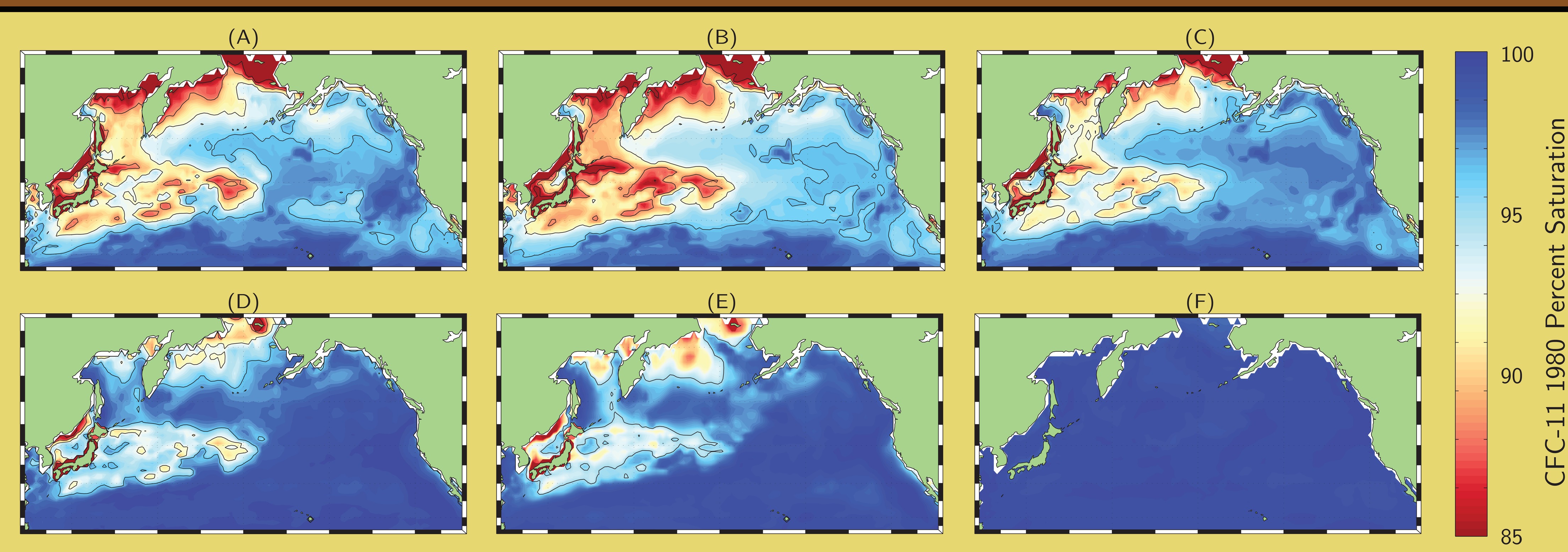
- Intrannual variability from seasonality of temperature, salinity, piston velocity, and mixed layer depth
- Month of greatest undersaturation (dashed line above) dependent on gradient in temperature and mixed layer depth.

Result: Spatial variability



- Undersaturation occurs in every ocean basin
- Occurs in regions of deep mixed layers, seasonal cooling and strong upwelling
- Degree of undersaturation greater than measurement uncertainty
- Can cause significant bias in ventilation time scales if not considered

Result: Sensitivity of saturation to physical processes



Numerical Experiments

(A) Control run: described above
(B) k_w scaled to 15.9 cm/hr, annual mean
(C) k_w scaled to 21.7 cm/hr, annual mean[7]
(D) No seasonal cycle in T/S
(E) No conc. difference in entrained waters
(F) Both (d) and (e)

Undersaturation sensitivity (North Pacific)

- Piston velocities k_w control magnitude of undersaturation (B, C)
- In areas of deep mixed layers and strong cooling, higher wind speeds drive waters closer to saturation in winter (A, B)
- Seasonal variability and mixed layer entrainment are the dominant causes of saturation (D, E, F)

References

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Discussion

Summary

- We present global maps of saturation for CFC-11, CFC-12, and SF6
- Oceanic ventilation sites with deep winter mixed layers tend to be undersaturated
- Seasonal cycle and entrainment control undersaturation (about equal contribution in North Pacific)

Future Work

- Use hindcasts from physical run to introduce interannual variability
- Quantify the effect of an undersaturated boundary on estimated ventilation ages and anthropogenic CO_2