Decode large-scale reorganization of atmosphere (& ocean) to understand how critical climate feedbacks work.

Interaction between:

cryosphere
atmosphere
hydrosphere

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Key aspects of D-O events,

1. ~1,500 year cycle
2. asymmetry between warming & cooling.
3. phase difference between hemispheres.

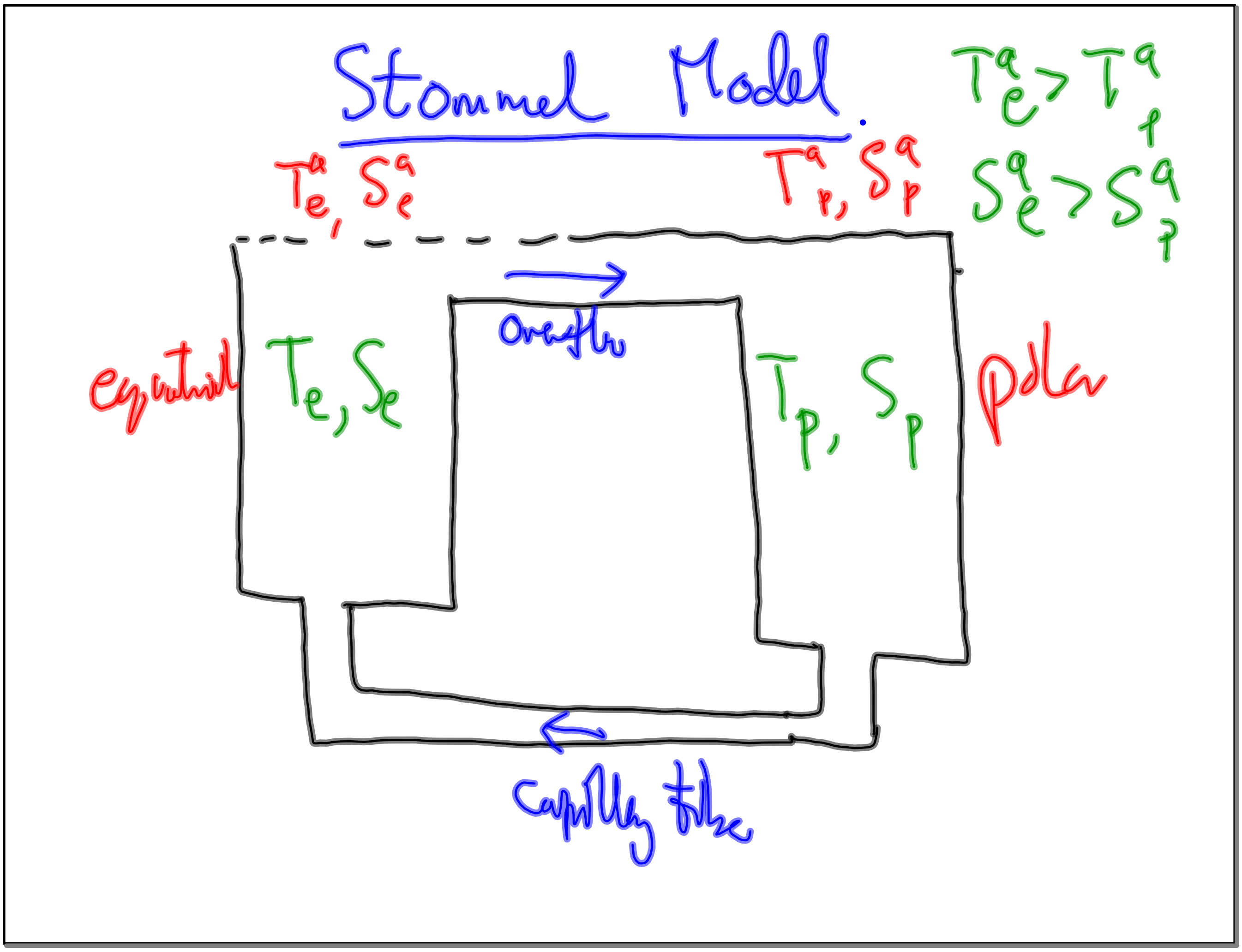
Debate: What causes the D-O events

2008: Clement & Peterson

Accepted: $\boxed{\text{ocean circulation is involved.}}$

Thermohaline Circulation.

related to: MOC – meridional overturning circulation


Stommel Model
$T_e^a > T_p^a$
$S_e^a > S_p^a$
T_e^a, S_e^a
T_p^a, S_p^a
equatorial
T_e, S_e
T_p, S_p
polar
overflow
capillary tube

Flow $\Phi = \gamma \frac{\rho_p - \rho_e}{\rho_0}$

ρ_p = density of pollution.

ρ_e = " " env "

ρ_0 = reference density

Equation of state,

$$\rho = \rho_0 \left(1 - \alpha_T (T - T_0) + \alpha_S (S - S_0)\right)$$

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Idea: form DES based on 2 effects:

1. left alone, relax to atmospheric temperature & salinity
2. flow in either direction driven by gradients.

Heat & salt balances:

$$V_p \frac{dT_p}{dt} = C_p^T (T_p^a - T_p) + |\psi| (T_e - T_p)$$

$$V_e \frac{dT_e}{dt} = C_e^T (T_e^a - T_e) + |\psi| (T_p - T_e)$$

$$V_p \frac{dS_p}{dt} = C_p^S (S_p^a - S_p) + |\psi| (S_e - S_p)$$

$$V_e \frac{dS_e}{dt} = C_e^S (S_e^a - S_e) + |\psi| (S_p - S_e)$$

$$R_T = C_T^p / V_p = C_T^e / V_e$$

$$R_s = C_s^p / V_p = C_s^e / V_e$$

$$\Phi = \gamma \left[\alpha_T (T_e - T_p) + \alpha_s (S_p - S_e) \right]$$

Next step: derive eqns. for

$T = T_p - T_e$ & $S = S_p - S_e$

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Can reduce to a 2D system of equations:

$$\frac{dT}{dt} = R_T\left(T_p^4 - T_e^4\right) + R_T\left(T_e - T_p\right) + \gamma\left[\frac{|\alpha_T T - \alpha_S S|}{V_p} + \frac{|\alpha_T T - \alpha_S S|}{V_e}\right] T$$

End up w/:

$$\frac{dT}{dt} = R_T \eta - R_T T - \gamma |\psi| \left(\frac{V_e + V_p}{V_e V_p} \right) T$$

$$\frac{dS}{dt} = R_S \zeta - R_S S - \gamma |\psi| \left(\frac{V_e + V_p}{V_e V_p} \right) S$$

Non-dimensionalize.

After much algebra:

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$$\boxed{\begin{aligned} \frac{dT}{dt} &= \eta_1 - T(1 + |T-S|) \\ \frac{dS}{dt} &= \eta_2 - S(\eta_3 + |T-S|) \end{aligned}}$$

$T = T_e - T_p$, $S = S_e - S_p$

$\eta_1 \propto T_e^a - T_p$, $\eta_2 \propto S_e^a - S_p^a$

$\eta_3 = R_S / R_T$

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Fixed pants: set RHS=0.

$$\eta_1 - T(1+|T-S|)=0$$

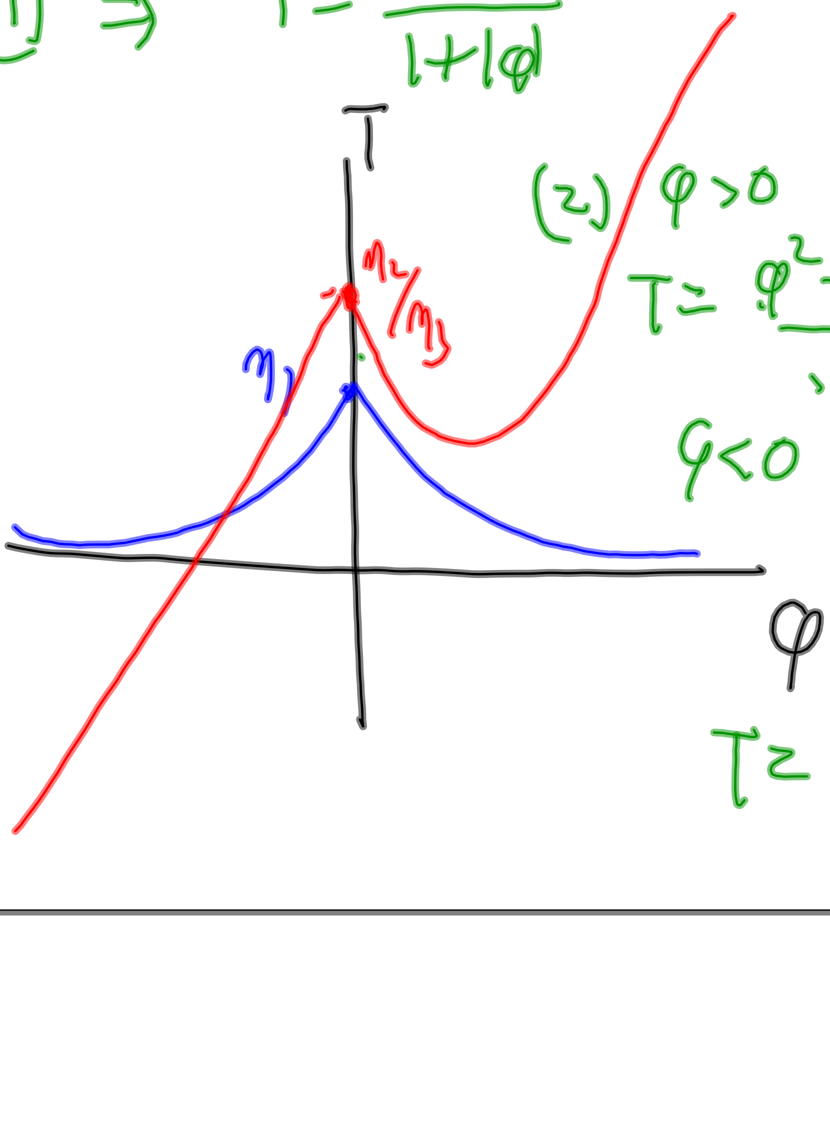
$$\eta_2 - S(\eta_3+|T-S|)=0$$

Change variables: $\varphi = T-S$, $T=T$

(1) $\eta_1 - T(1+|\varphi|)=0$

(2) $\eta_2 - (T-\varphi)(\eta_3+|\varphi|)=0$

(1) $\Rightarrow$ $T = \dfrac{\eta_1}{1+|\varphi|}$



(2) $\varphi > 0$

$$T = \frac{\varphi^2 + \varphi\eta_3 + \eta_2}{\varphi + \eta_3}$$

$\varphi < 0$

$$T = \frac{\varphi^2 - \varphi\eta_3 - \eta_2}{\varphi - \eta_3}$$

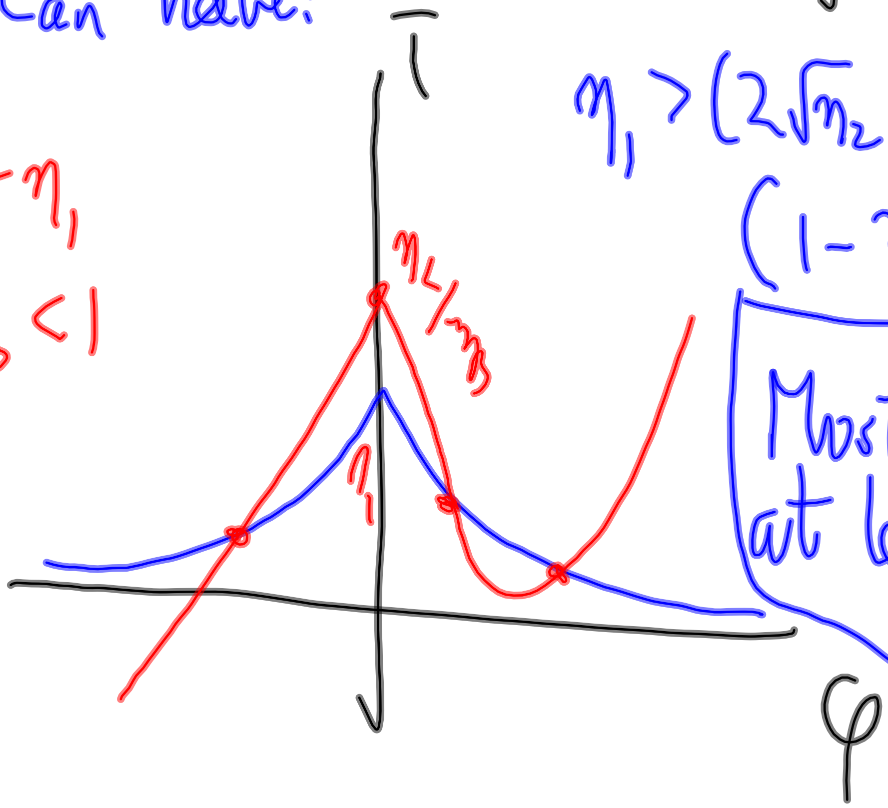
Can have:

Conditn for 3 f.p.'s:

$\eta_1 > (2\sqrt{\eta_2} - \eta_3) \times (1 - \eta_3 + \sqrt{\eta_2})$

$1 < \eta_1$

& $\eta_3 < 1$



$\boxed{\text{Must have at least one f.p.}}$