Thermohaline Circulation Stability: A Dynamical Systems Point of View

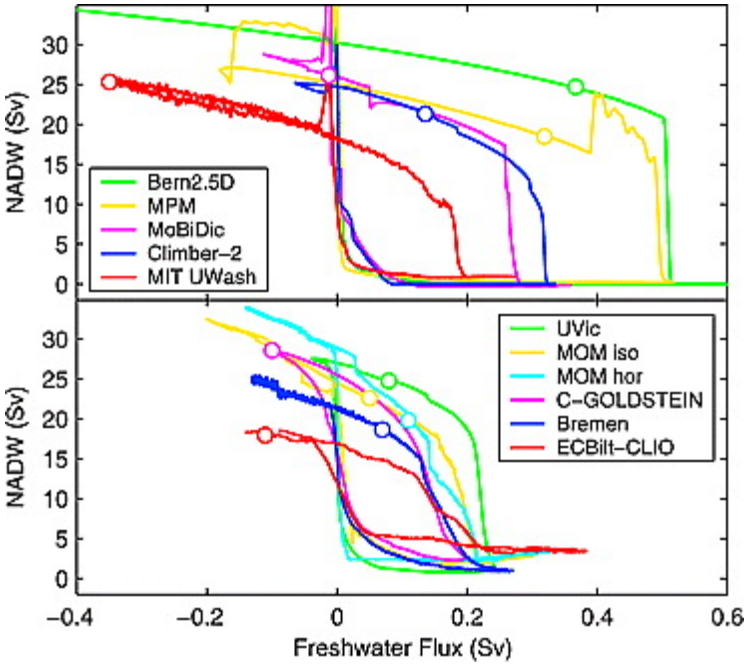
Wilbert Weijer

THC stability

- **THC stability largely determined by equilibrium structure**
- **Important questions:**
  - Is the current THC in, or close to, a regime of multiple equilibria?
  - If so, what would it take to “shut down” THC?

THC stability: what determines limit points?

- **Equilibrium structure reasonably well understood in qualitative sense**
- **Large quantitative differences between models**



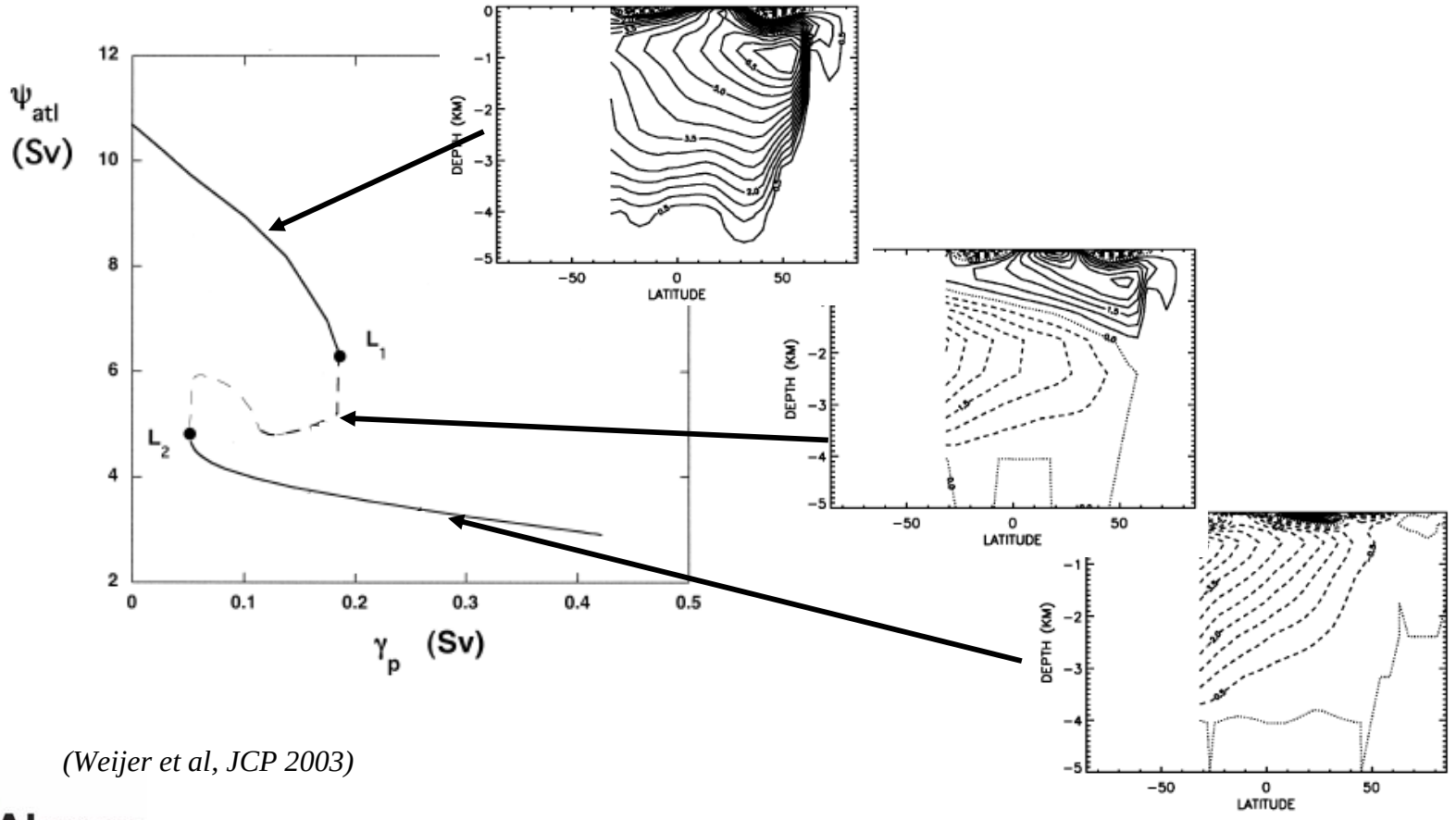
2D models

3D models

(Rahmstorf et al, GRL 2005)

THC stability: what determines limit points?

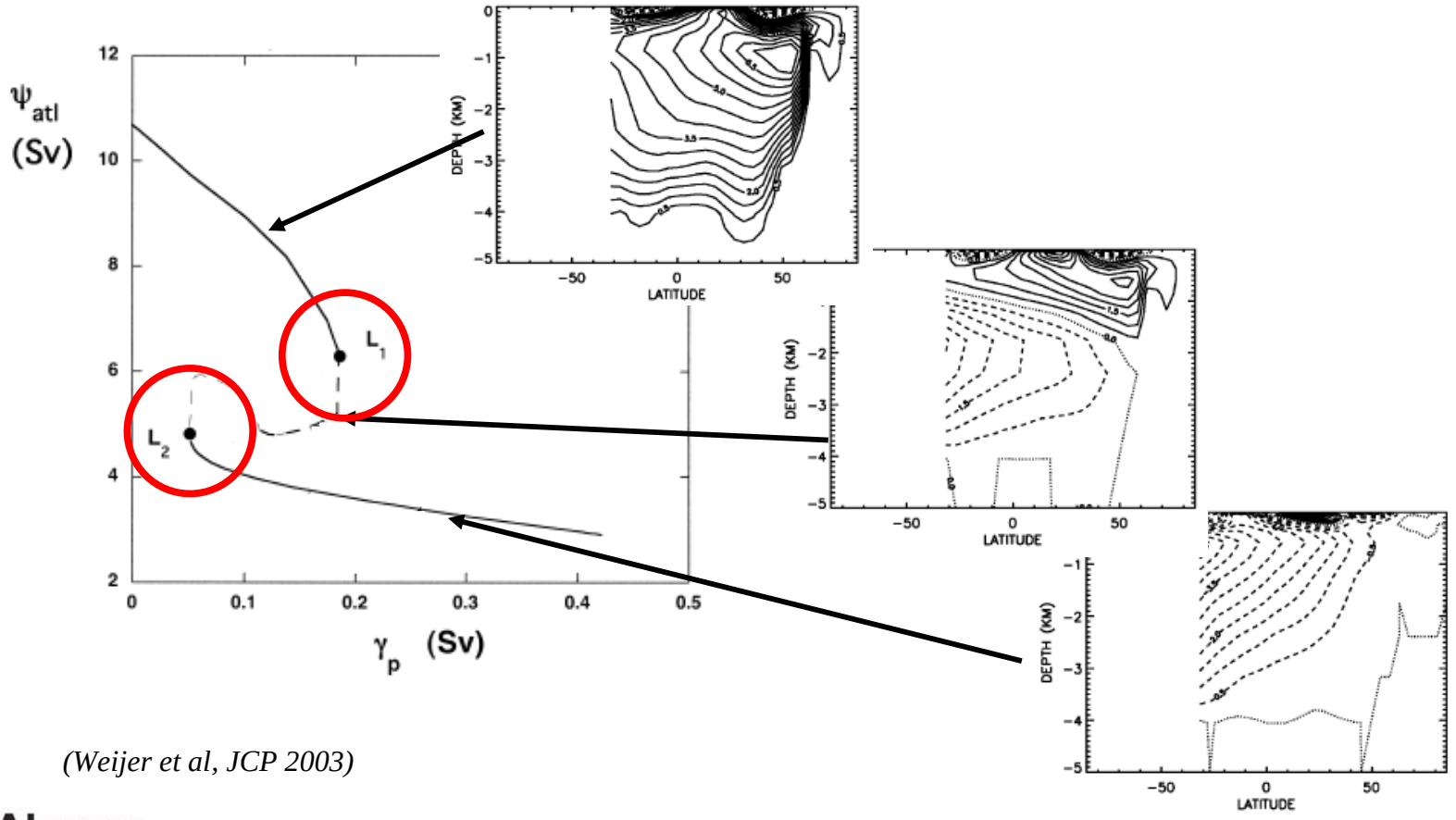
- **Hysteresis diagrams reflect underlying equilibrium structure**



(Weijer et al, JCP 2003)

THC stability: what determines limit points?

- **Critical points: limit points**



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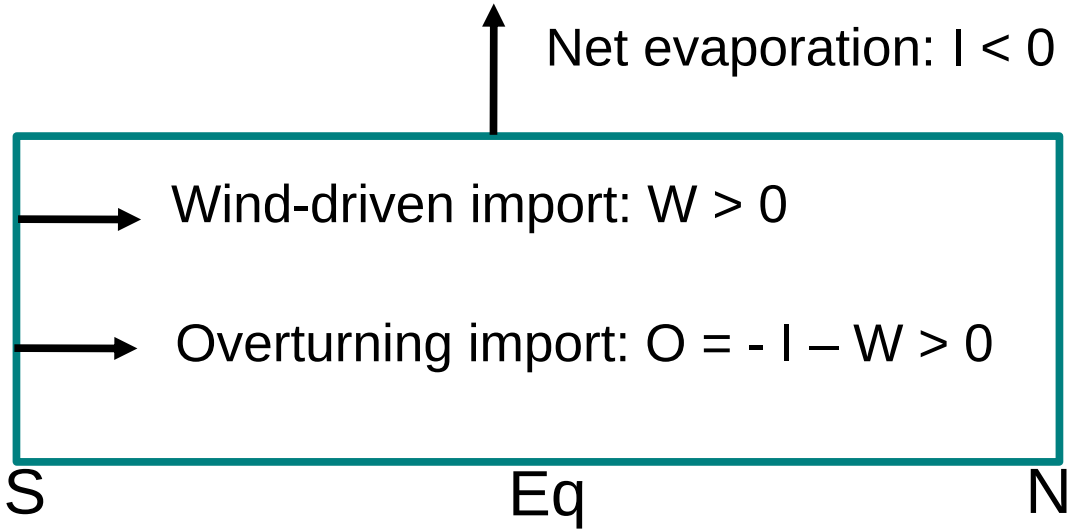
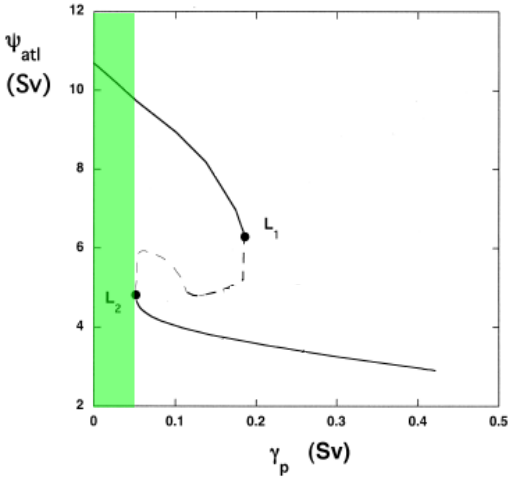
THC stability: what determines limit points?

- **L_2 determined by freshwater balance of the Atlantic:**
  - Mono-stable if THC salinifies





THC stability: what determines limit points?

- **L_2 determined by freshwater balance of the Atlantic:**
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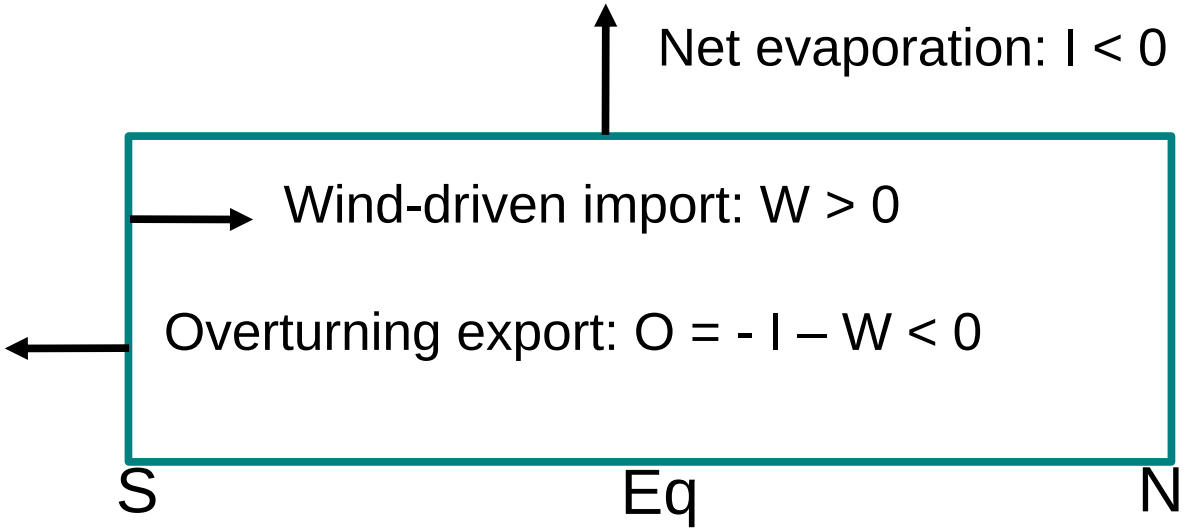
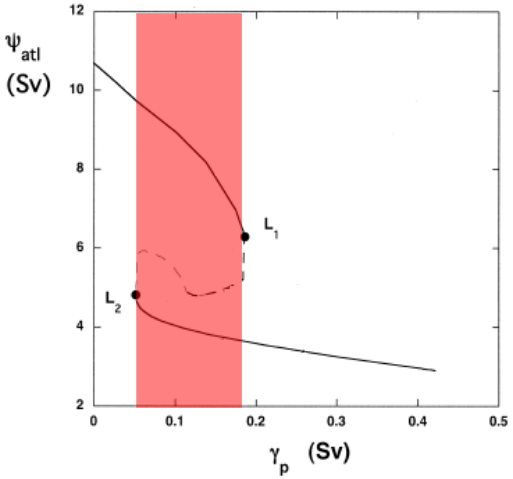




THC stability: what determines limit points?

- **L_2 determined by freshwater balance of the Atlantic:**
  - Mono-stable if THC salinifies
  - Bi-stable if THC freshens
- **Inversion studies (e.g., Weijer 1999):**
  - F_{35S} = + 7.0 Gg/s ⇨ THC freshens ⇨ bi-stable regime!

THC stability: what determines limit points?

- **L_1 diagnosed by buoyancy budget of the Atlantic?**
- **Rahmstorf (1996) model:**

$$\beta S_0 F_{crit} = 1/4\ k\ (\alpha \Delta T)^2 = \tfrac{1}{2}\ \alpha\ Q/\rho c_p$$

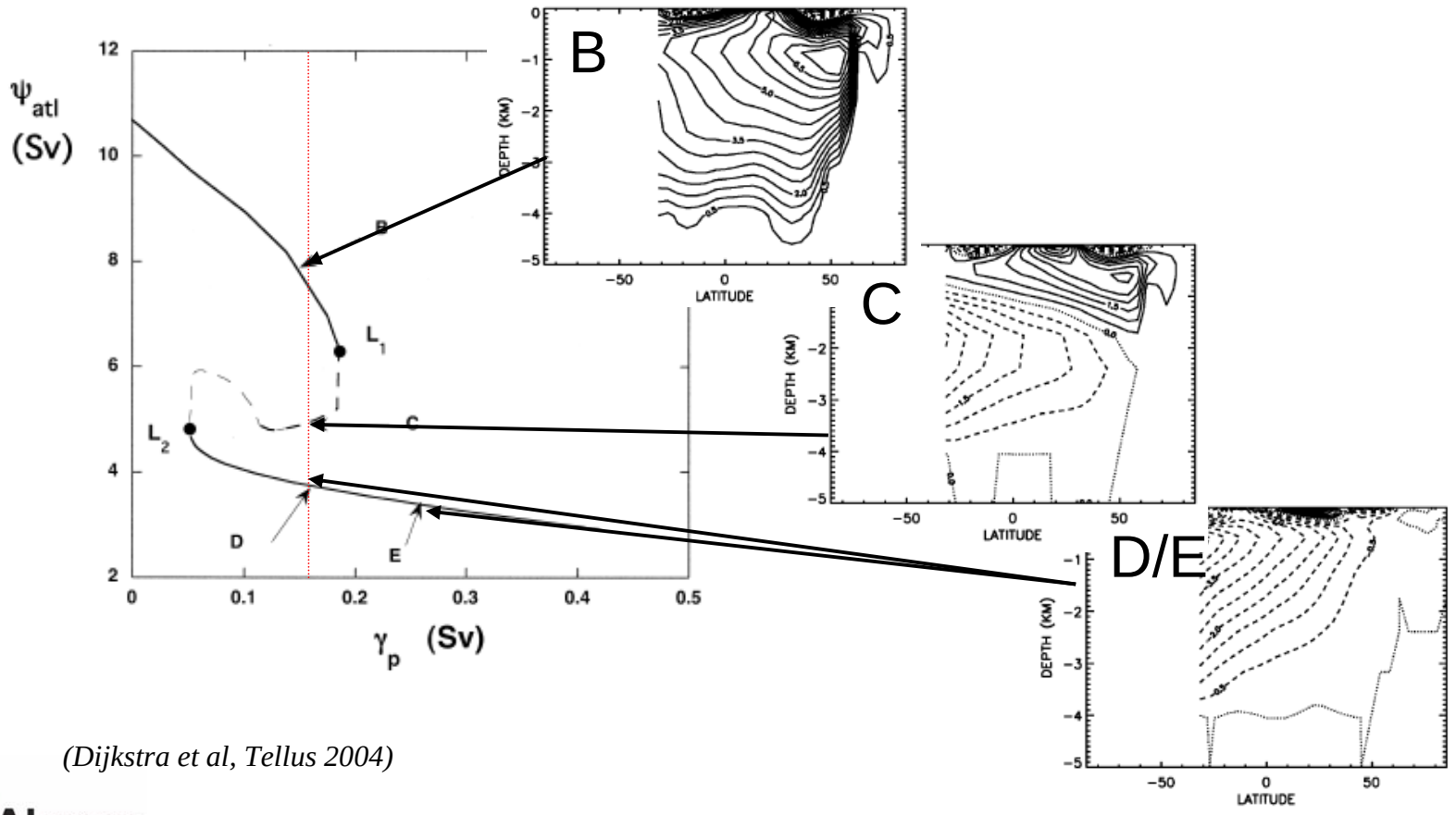
- **Buoyancy gain by freshening of THC = half buoyancy loss by cooling**
- **Inversion study:**
  - Q_{35S} = 0.63 PW ⇨ B^T = 3.2 x 10^7 kg/s
  - F_{35S} = 7.0 Gg/s ⇨ B^S = -0.5 x 10^7 kg/s

Transient perturbation threshold: What determines t_{crit}?

- **If in multiple-equilibria regime, what is the critical period t_{crit} of a given perturbation that will trigger a THC collapse?**

Transient perturbation threshold: What determines t_{crit}?

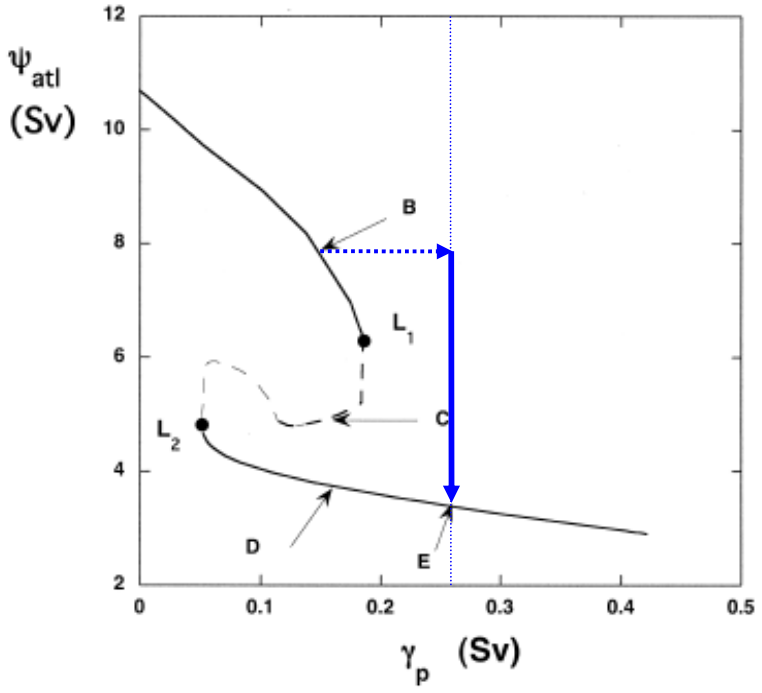
- Start from γ_p = 0.15 Sv



(Dijkstra et al, Tellus 2004)

Transient perturbation threshold: What determines t_{crit}?

- **Apply perturbation: γ_p = 0.23 Sv for t_m = infinity**



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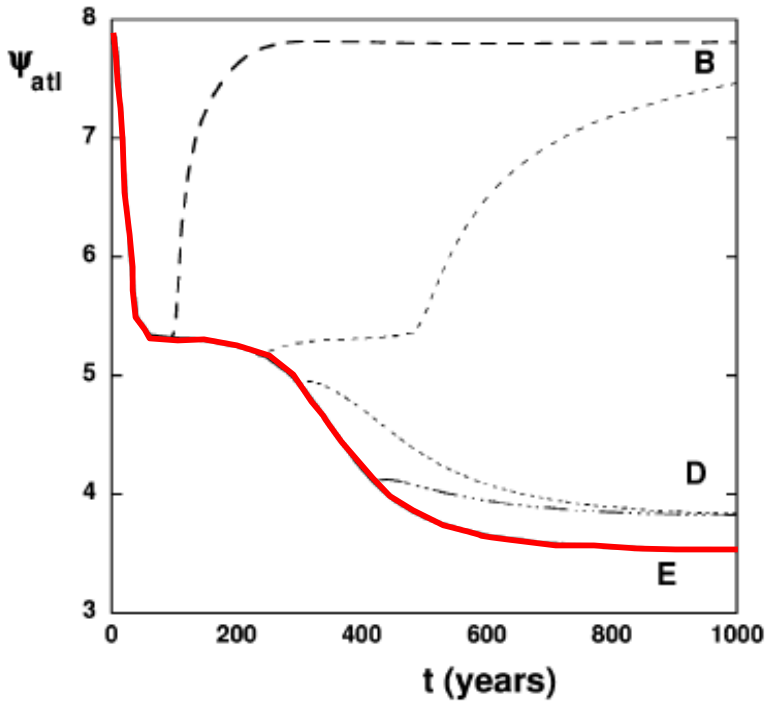
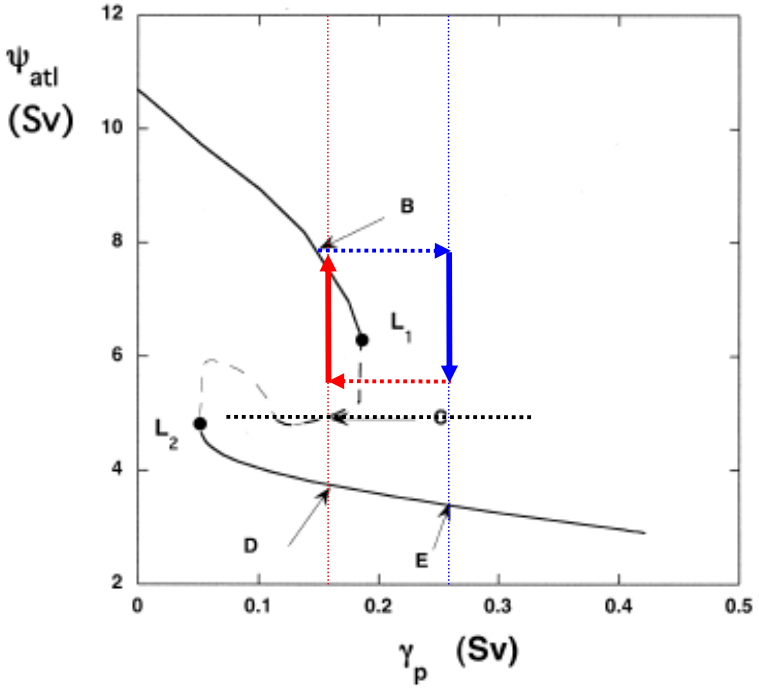


Transient perturbation threshold: What determines t_{crit}?

- **Apply perturbation: γ_p = 0.23 Sv for $t_m < t_{crit}$**



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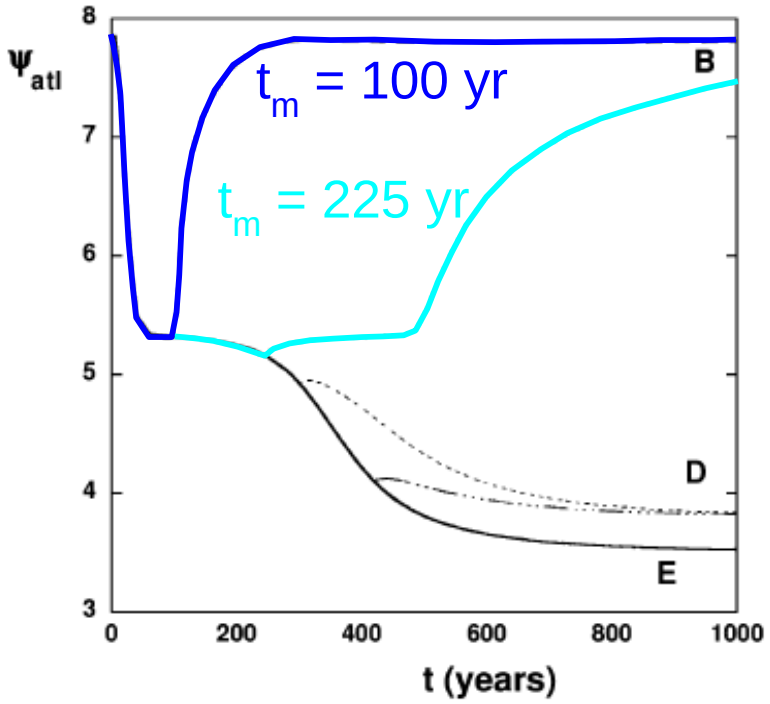

Transient perturbation threshold: What determines t_{crit}?

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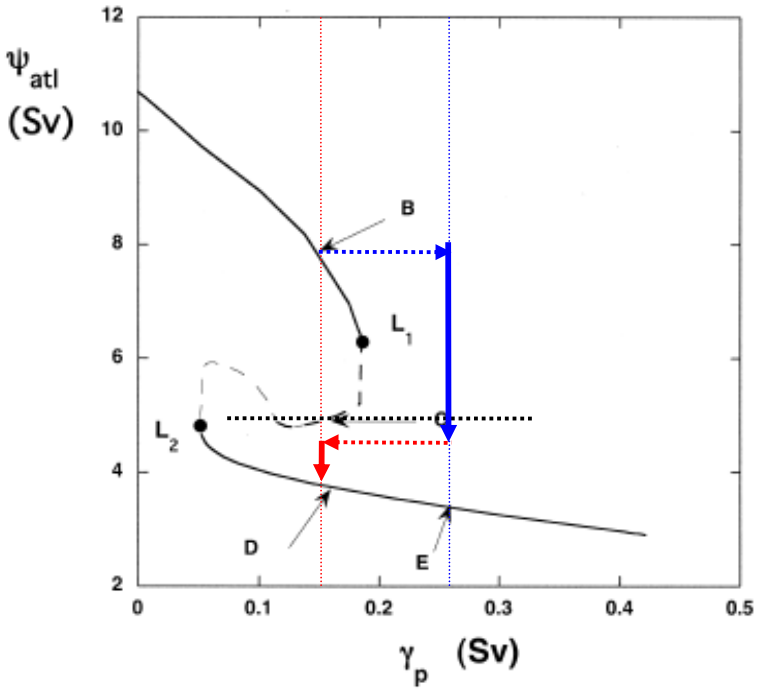

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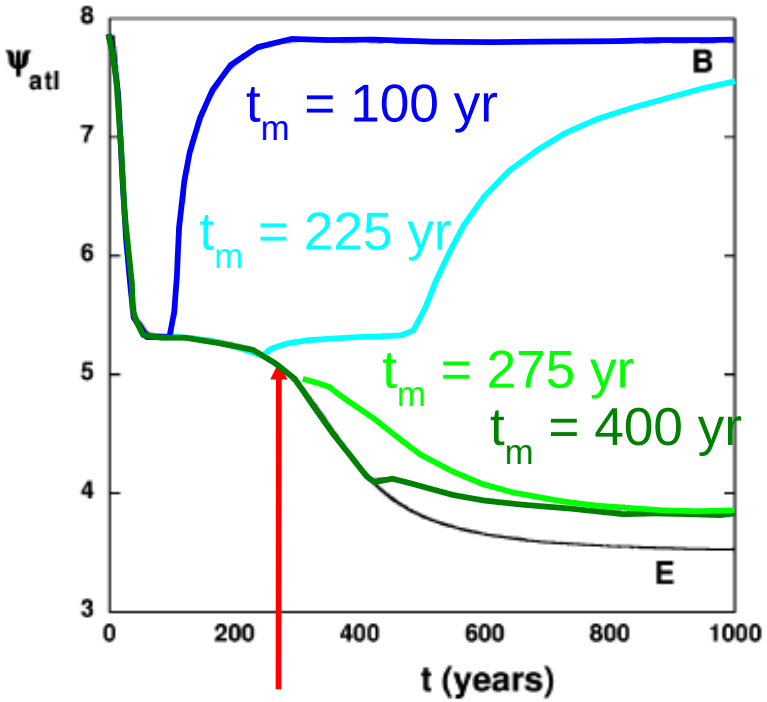
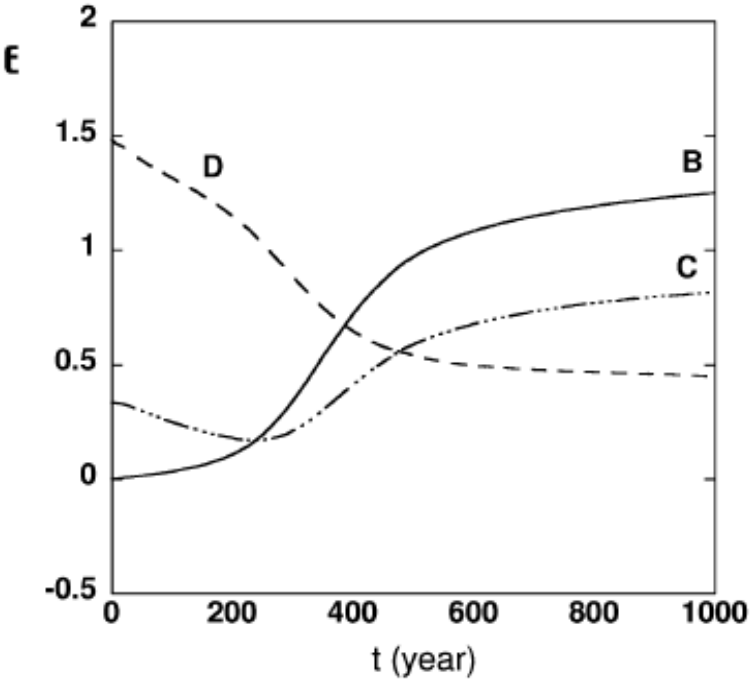


t_{crit} between 225 and 275 years

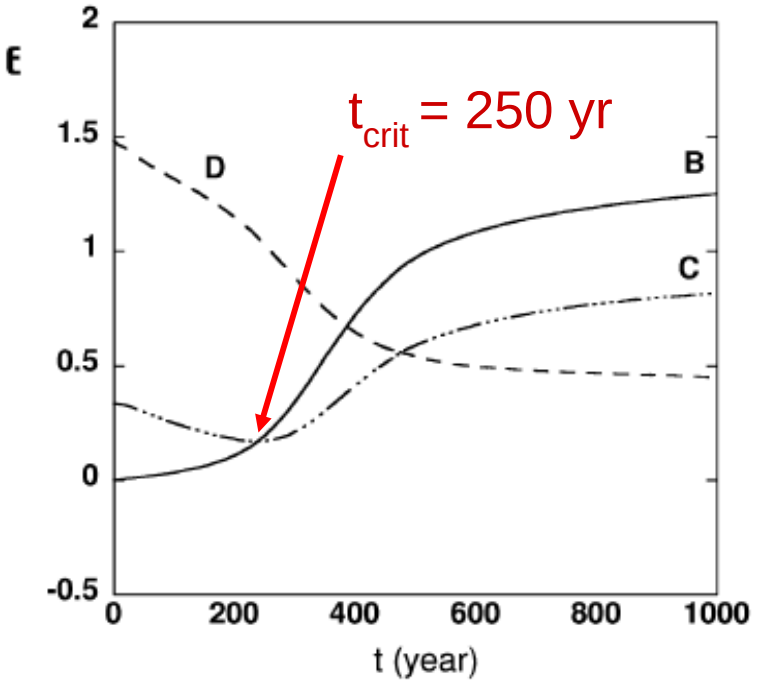
Transient perturbation threshold: What determines t_{crit}?

- **Unstable equilibrium C is on separatrix of basins of attraction of B and D**
- **Define "distance" between transient state and equilibria B, C and D as an *energy functional*: $E_i = < (\rho_i - \rho)^2 >$**
- **Calculate E_i for transition from B to E**



Transient perturbation threshold: What determines t_{crit}?

- **Minimum distance with respect to unstable equilibrium C: 250 years**



Conclusions

- **THC stability determined by equilibrium structure**
- **Limit points**
  - Limit point 2 determined by freshwater balance (surface plus wind-driven)
  - Can limit point 1 be diagnosed by buoyancy budget?
- **Transient perturbation threshold**
  - Critical duration of perturbation can be diagnosed by tendency of energy functional
  - Just one integration necessary, provided that all (including unstable!) equilibria are known