# Modeled and observed fast flow in the Greenland ice sheet

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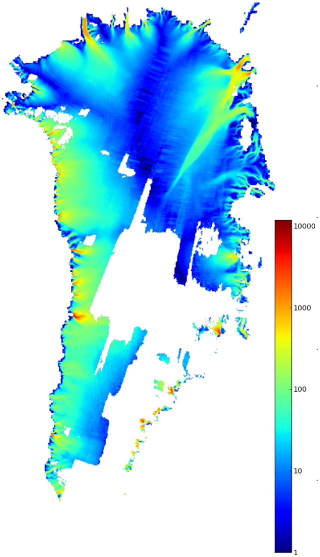
# Outline

# inSAR surface velocity observations

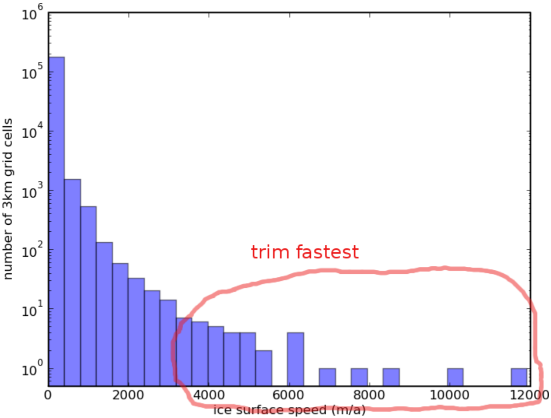
- RADARSAT SAR
- acquired Dec 2005 to Apr 2006
- inSAR and speckle-tracking to produce surface velocity[a] on 500 m grid
- comparison to GPS suggests errors $<$ 10% for $>$ 100 m/a ice; observation error much less than model error below
- here: averaged onto 3 km grid
- method: 3 km cell is kept if at least 20% of 500 m cells have values
- 71.6% area coverage on 3 km grid




[a] Joughin et al. [2002,2008,in preparation]

# “fast flow” versus fastest flow

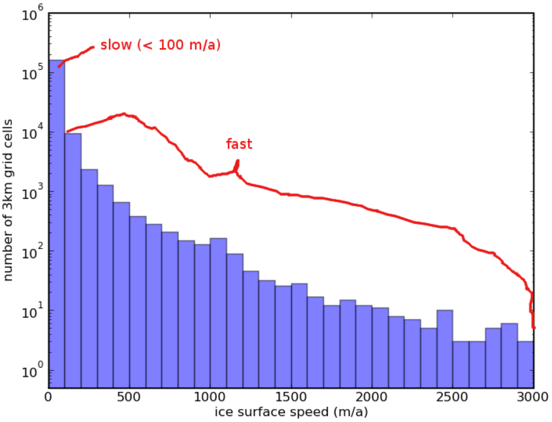
- histogram of observed surface speed on 3 km grid ↓




- exist 3 km cells with $\approx$ 12 km/a surface speed
- . . . but few, and in tight, steep fjord topography
- e.g. only *eleven* 3 km cells with average speed above 5000 m/a
- note log scale on $y$-axis
- this talk: we trim off $>$ 3000 m/a cells, for comparison to whole ice sheet model

# goal: model the fast flow

- **Definition.** *fast flow* means 100 m/a to 3000 m/a surface speed; *slow* means $<$ 100 m/a
- **Goal**: we want a model for the present dynamical state of Greenland ice sheet, with few tunable parameters, which comes close to this observed histogram →



# goal: model the fast flow 2

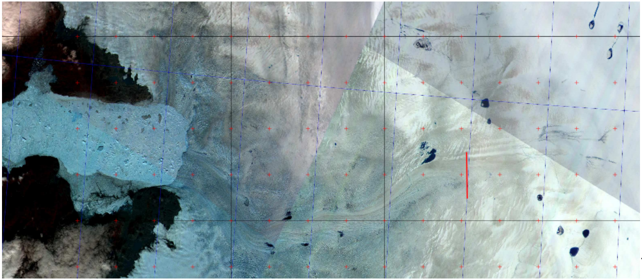
- why this particular goal?
  - * fast-flowing regions will dominate century- and millenium-scale dynamical response to climate changes
  - * . . . especially sea level contribution
  - * shallow models have had trouble with fast flow
  - * a specific modeling goal focusses the mind

# goal: model fast flow 3

- is matching surface velocity enough?
  - no
  - ...but inSAR surface velocities are the highest-dimensional existing dynamical info on the present state
- why not just do inverse modeling of surface velocities?
  - yes, we *will* use inversion to get initial state for predictions
  - ...but, for prediction and scenarios, we need a model with evolving geometry, temperature, basal resistance, etc.

# the resolution challenge

- fast flow occurs
  - near, within, and over marginal mountain ranges
  - along subglacial trenches
- therefore shallow assumptions need to be removed
- *and* resolution needs to be high


[1]

5km grid (red +) and channel width (red segment) though which much of the Ilulissat (Jakobshavn) Glacier is fed

[1] composite ASTER image, M. Fahnestock and M. Truffer

# this talk: a small parameter study

- a small parameter study[2] using a hybrid shallow model
- results from eight whole Greenland ice sheet model runs
- each run: 100 model years on 3 km grid
- before start of run: spin-up in steady present climate for total of 110 k model years[3]
- each run starts from present bed elevation and thickness (Bamber et al 2001)
- assumed steady, present climate:
  - Fausto et al. (2008) temperature parameterization
  - PARCA accumulation map (van der Veen et al. 2001)
  - positive degree day scheme for surface mass balance
- at end of each run: compare surface velocities to observed

[2] more below . . .

[3] On grids refining from 10 km to 5 km to 3km. Purpose: to equilibriate ice and bedrock temperature, in balance with advection.

# Outline

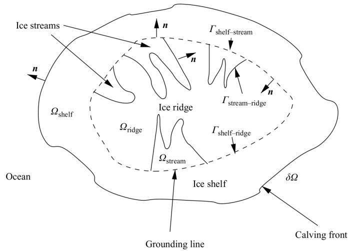
# shallow model ideas

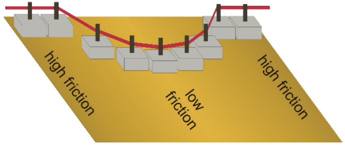
- the Greenland ice sheet has aspect ratio $\approx 1/1000$
- fastest-flowing parts include significant bed topography so shallow models must miss something (acknowledged!)
- "shallow" models for grounded ice include
  - shallow ice approximation (SIA): gravity-driven lubrication flow, sticking to bed and shearing in vertical planes; *no sliding in the SIA as understood here*
  - dragging shallow shelf approximation (SSA) for ice streams: gravity-driven viscous membrane sliding over variable-strength bed ("till")

# shallow model ideas 2

## C. Schoof (2006) insight, for diagnostic case

SSA + (plastic till) = (well-posed free boundary problem for location and velocity of sliding)



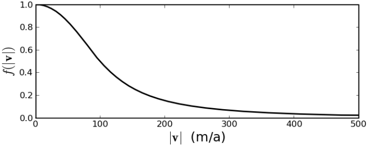

- till strength/resistance given by yield stress $\tau_c$: $\vec{\tau}_b = \tau_c \mathbf{v}_b / |\mathbf{v}_b|$
- scheme is a whole ice sheet form of D. MacAyeal's individual ice stream models (1989)

# Parallel Ice Sheet Model (PISM)

- SIA and SSA velocity solutions, combined or separate
- thermomechanically-coupled
- parallel:
    * 3 km grid runs here done on 64, 128, or 256 processors at Arctic Region Supercomputing Center, Fairbanks
    * $501 \times 935 \times 201$ ice grid; $\approx$ 300 million temperature and velocity unknowns
    * all runs here total $\approx$ 8000 processor-hours
    * is that a lot of processor-hours?
- homepage `www.pism-docs.org`

# PISM: Schoof ideas adapted to prognostic modeling

- SSA-as-a-sliding law (Bueler et al. 2009)
  - * $\mathbf{U} = f(|\mathbf{v}|)\mathbf{u} + (1 - f(|\mathbf{v}|))\,\mathbf{v}$, where
  - * $\mathbf{v}$ is SSA solution
  - * $\mathbf{u}$ is SIA solution
  - * $\mathbf{U}$ is model velocity used in mass continuity and energy conservation equations




- pseudo-plasticity:

$$\vec{\tau}_b = \tau_c \frac{\mathbf{v}_b}{|\mathbf{v}_b|^{1-q}(100\ \text{m/a})^q}$$

- surround ice sheet by thin notional ice shelf to maintain ellipticity of SSA

# PISM: (*newly*!) polythermal by enthalpy method

- Aschwanden and Blatter (2008 JGR; in preparation 2009)
- $E$=enthalpy=(sensible thermal $+$ latent thermal $+$ potential of pressure)
- temperature $T$ and liquid water fraction $\omega$ are functions of enthalpy and pressure, for cold and temperate ice:

$$T = T(E, p), \qquad \omega = \omega(E, p)$$

- *think*: $E = E(t, x, y, z)$ is the primal thermal variable in conservation of energy equation
- solve conservation of energy equation for $E$

# PISM: basal thermo-mechanical model

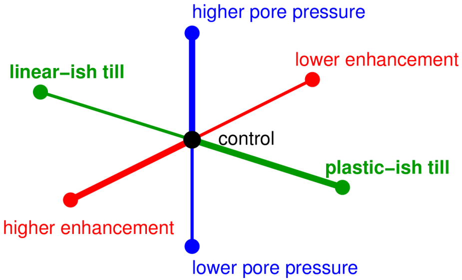
- yield stress determined by Mohr-Coulomb:

$$\tau_c = c_0 + (\tan\phi)\,(\rho g H - p_w)$$

- $c_0 = 0$
- basal melt rate from 1 % $\omega$ rule (Greve 1997)
- pore water pressure $p_w$ is local, time-integrated function of basal melt rate
- till friction angle $\phi$ determined by bed elevation below sea level
  - motivated by presumed marine history of sediment below sea level (Huybrechts and de Wolde 1999)
  - $\phi = 5^\circ$ at -700 m and below
  - $\phi = 20^\circ$ at +300 m and above
  - linear between
- model description done!

# Outline

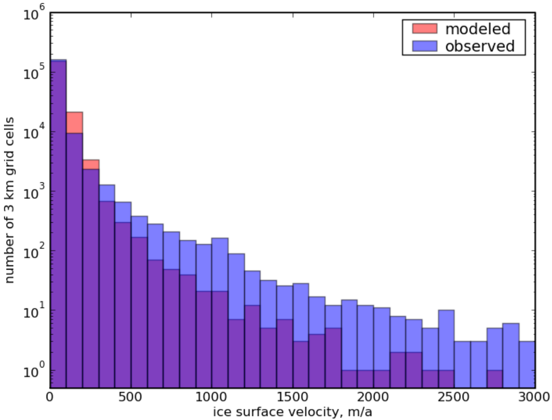
# parameter study: control run plus six variations

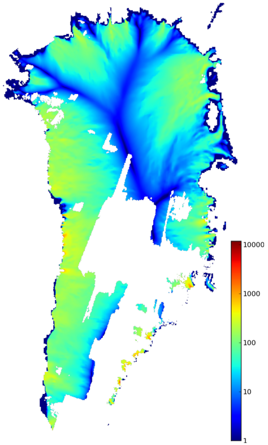



- enhancement factor $e$: 1, 3 , 5
- exponent $q$ in basal power law; $0$=plastic, $1$=linear: 0.50, 0.25 , 0.10
- limit $p_{\text{max}}$ on pore water pressure; % of overburden: 95, 98 , 99
- first directly affects only SIA velocities, last two directly affect only SSA velocities

# Control run results

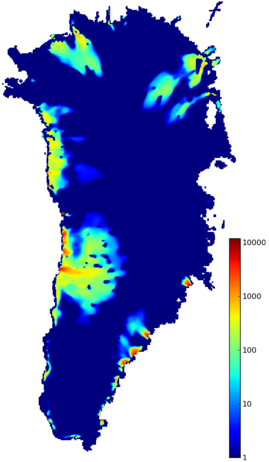
- enhancement factor=3, limit on pore water pressure=98%, exponent in basal power law=0.25



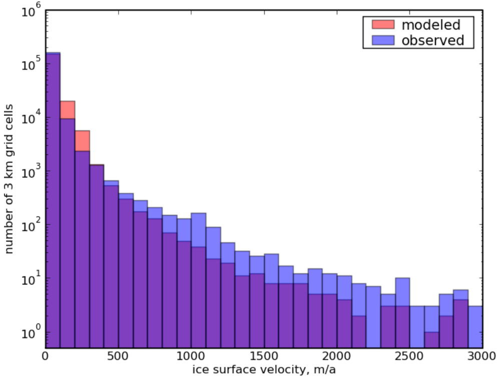
# Control run results 2: how much is from sliding?

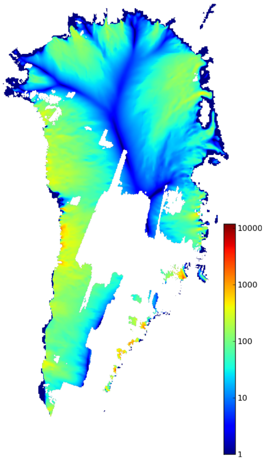
- sliding speed, on same velocity scale
  $\longrightarrow$



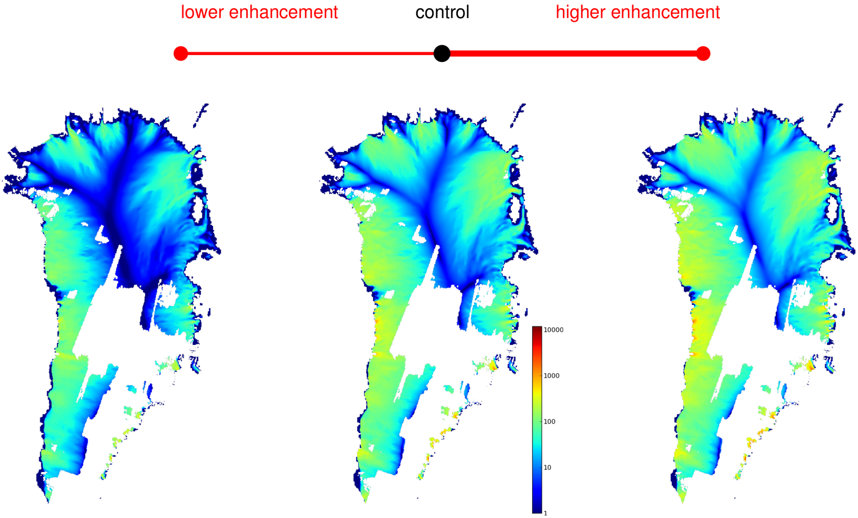
# Control run results 3: what if there is no sliding at all?

- enhancement factor=3 and no SSA computation (no sliding; SIA only; "sub-control" run?)
- SIA-only models with no sliding give reasonable distribution of fast flow, if done on 3 km grid
- distinction from with-SSA-sliding runs seen in time-dependence . . . another talk . . .



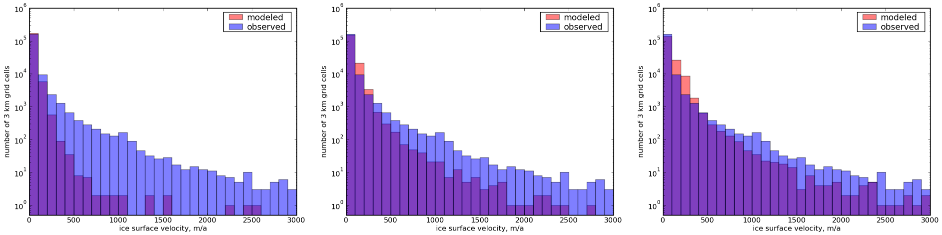



# Enhancement factor axis

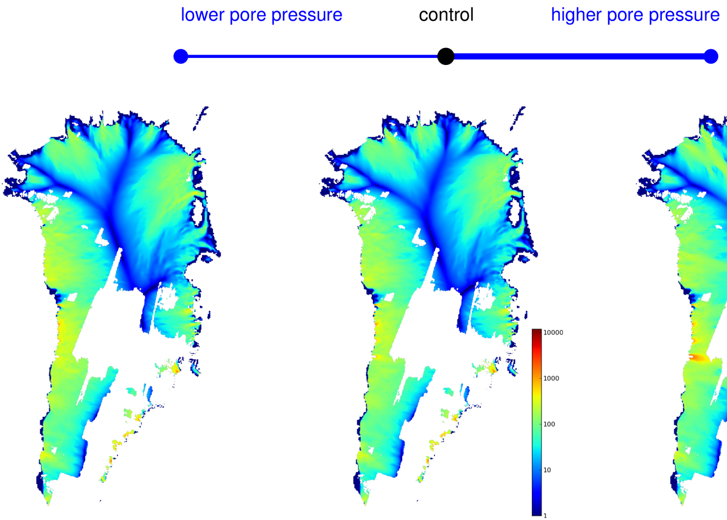


# Enhancement factor axis 2

lower enhancement   control   higher enhancement

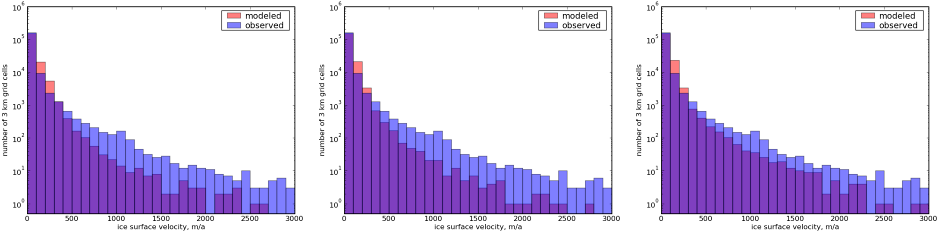


# Allowed pore water pressure axis

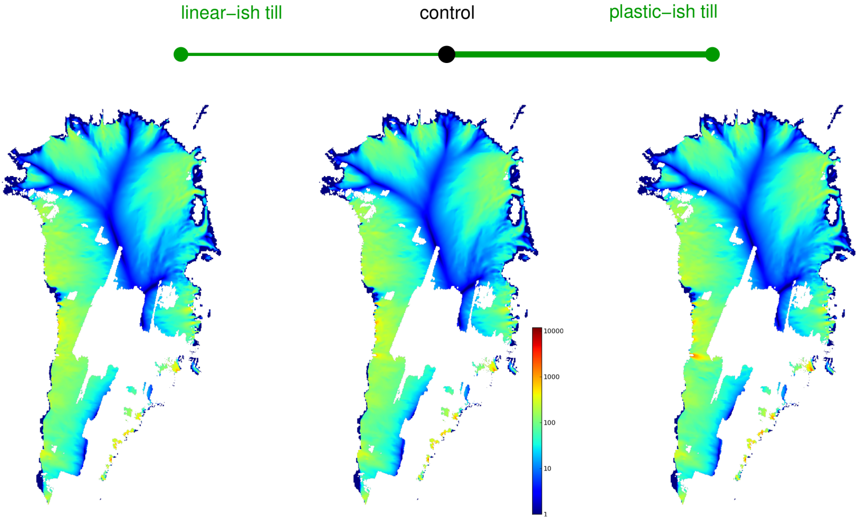


# Allowed pore water pressure axis 2

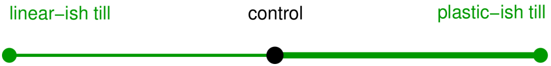
lower pore pressure — control — higher pore pressure

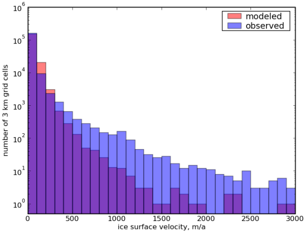


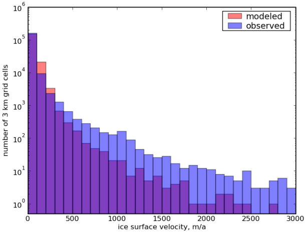
# Plasticity (power law power) axis

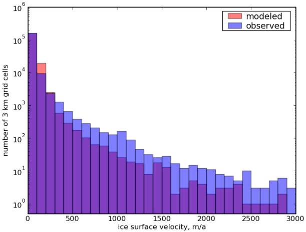


# Plasticity (power law power) axis 2



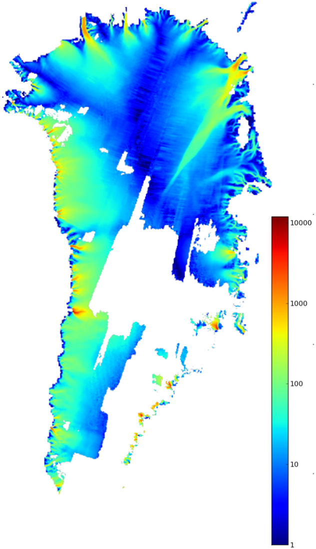
# Summary of results

- high resolution is a key to modeling fast flow, regardless of shallowness
- SIA models can yield fast flow, but then too much is in the 100 m/a to 300 m/a range, compared to observed
- evidence here for two parameters effecting fast flow in Greenland:
  - * high subglacial water pressure
  - * plastic or nearly-plastic till behavior

# Conclusions

- the SSA is a shallow sliding law
    - which balances basal shear by membrane stresses
    - ...but it requires a parameterization of subglacial “wet and soft” processes
- enthalpy-formulated polythermal ice models are
    - easy to implement, and
    - add credibility to conservation of energy and drainage models
- parallelism is effective
- 3 km grid or finer Greenland ice sheet models with ice streams *will contribute to IPCC AR5*
- next steps:
    - inverse modeling for initialization
    - better basal and surface process modeling
    - more complete stress balances for outlet glaciers
- The End

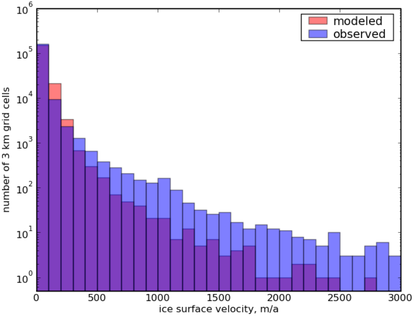
# inSAR surface velocity for Greenland



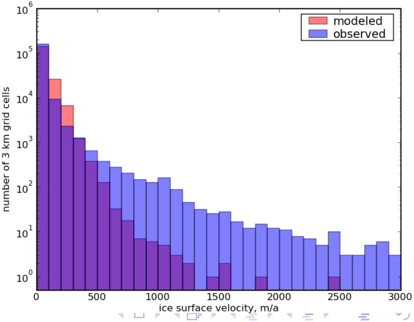
# Extra: Control run results 4: what happened at 20 model years?

- previous results were at 100 model years; here is an example at 20 model years

control run at 100 a



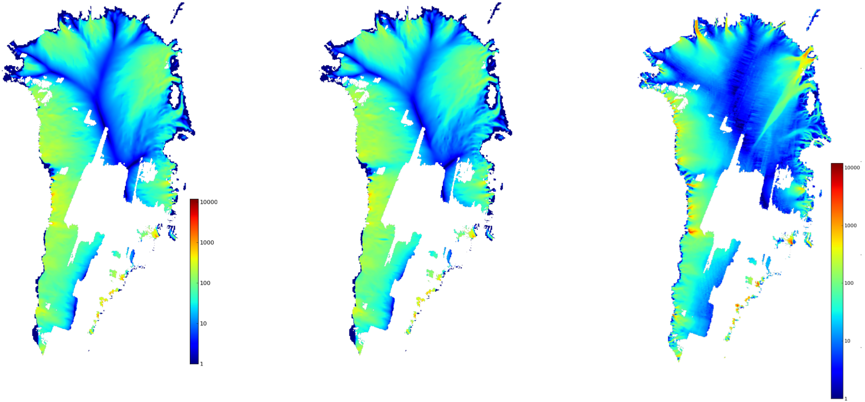

control run at 20 a



# Extra: Geothermal high at source of NE Greenland

- following Fahnestock et al (2001), try a 970 mW m-2 “hot spot”

control hotspot observed



# PISM, cont.

- verifiability
  - construction of verification tests main focus during development (Bueler et al. 2005,2007)
  - tests for SIA, SSA, and thermo- components
  - can be checked at any time
- derivability
  - its a big C++ program
  - Potsdam group (Levermann et al.) has PISM-PIK Antarctic model with improved ice shelf dynamics and fracture-based calving

# PISM: polythermal by enthalpy method 2

- conductivity of polythermal ice:

$$k = \begin{cases} k_{\text{ice}}, & T(E,p) < T_{\text{pmp}} \\ 0, & T(E,p) = T_{\text{pmp}} \end{cases}$$

- flow law is Paterson & Budd (1982) with Lliboutry & Duval (1985) dependence on $\omega$
- cold-temperate transition surface (CTS) is boundary of $\omega > 0$ region
- …so we have no explicit representation of CTS as a surface
- …and no restriction on evolving CTS shape