Fourth Annual Conference on Carbon Capture & Sequestration

Developing Potential Paths Forward Based on the Knowledge, Science and Experience to Date

Ocean Sequestration

Simulation of Sinking CO_2 Hydrate Composite Plumes

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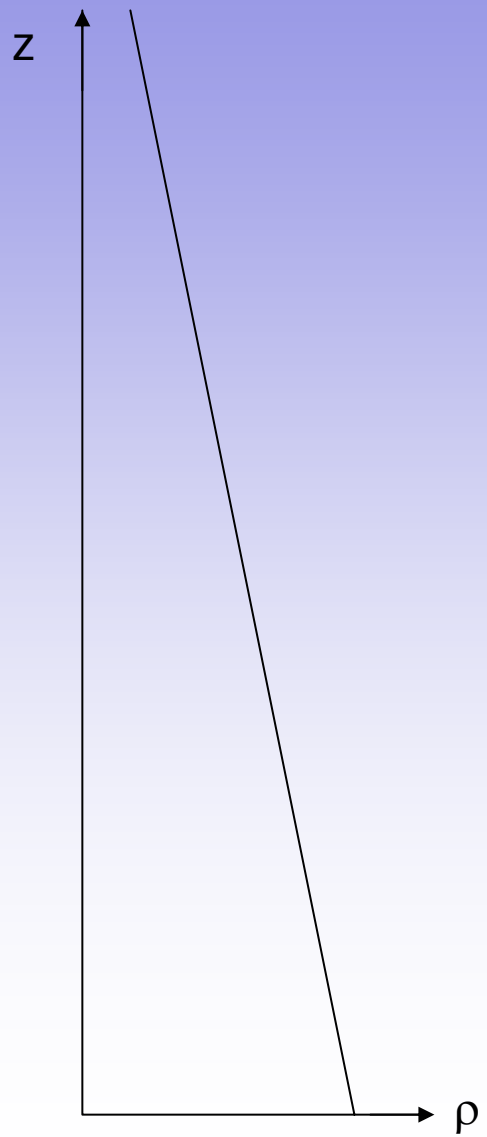
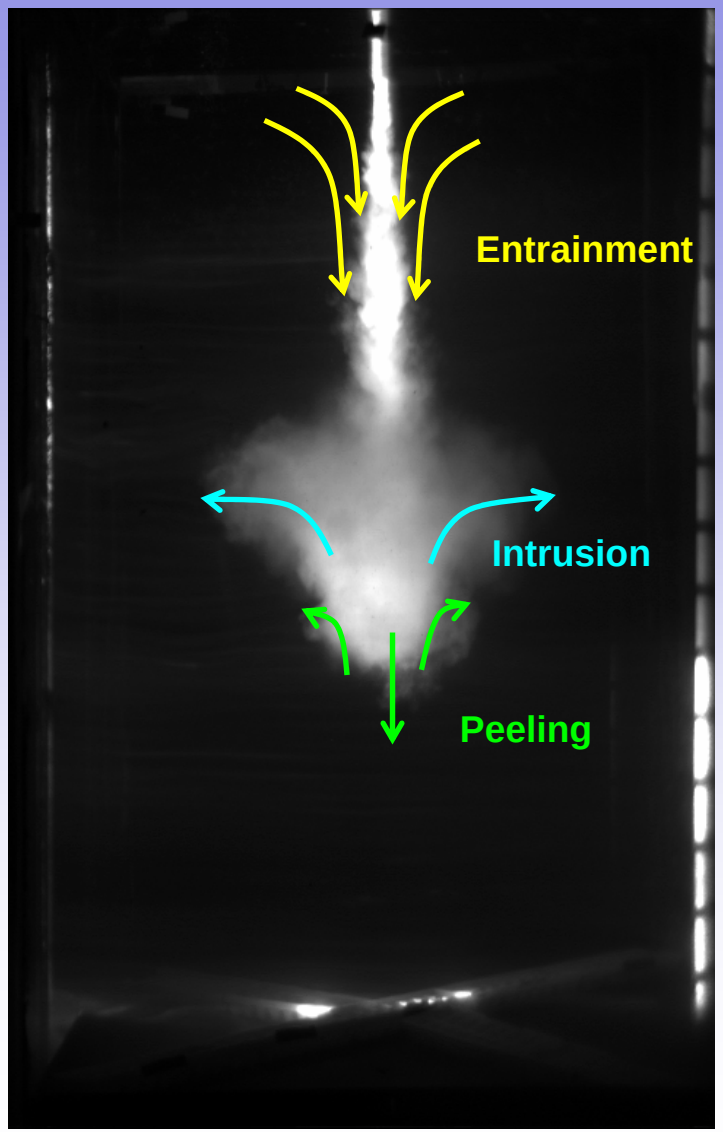
Motivation

- ORNL particles ~ 1g/s CO_2
- Typical power plant ~ 100 kg/s
- Large clusters of particles sink faster
  - plume effect
  - solute density effect

- Near field numerical simulation of two-phase (particle) plumes
  - Plume descent depth
  - Added dissolved inorganic carbon (DIC) concentration
  - Average pH change

Sinking particle plume - example





Buoyancy due to:

-Glass beads

-Brine

Behavior in

Stratified ambient:

-Entrainment

-Peeling

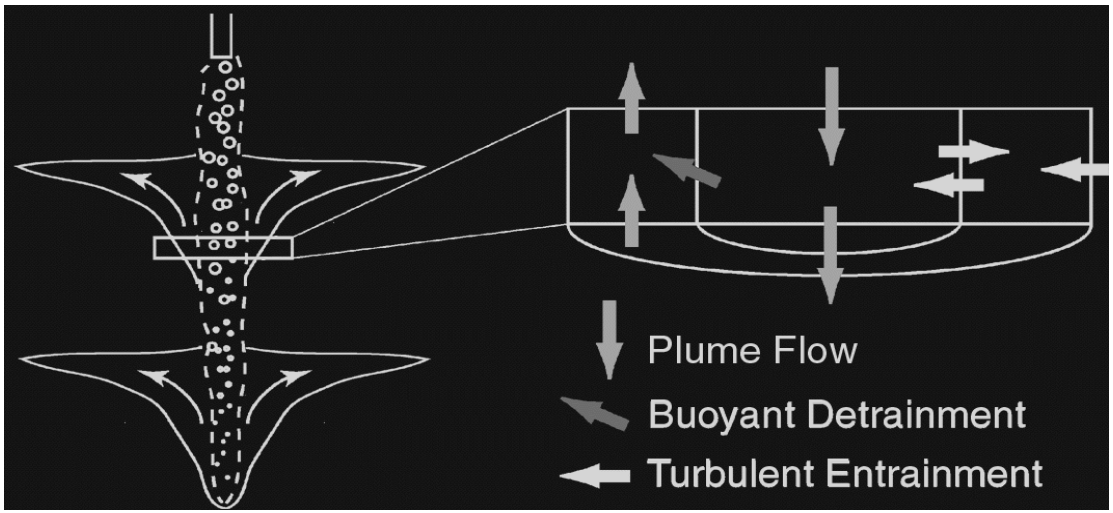
-Intrusion

Two-phase (particle) plume model

(Adams, Crounse, Wannamaker, Socolofsky)

- Initial value problem – integrated mass, momentum, buoyancy, thermal energy, dispersed phase fluxes
- Double plume structure – inner/outer

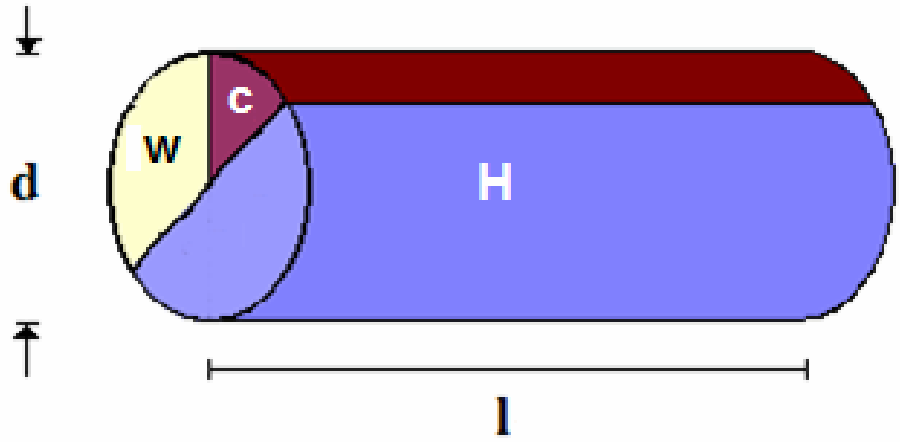
  (Asaeda and Imberger, 1993)



- Plume peeling algorithm (depends on dispersed phase slip velocity)
- Entrainment between inner/outer plume – iterative
- Particle behavior
- Solute density effect

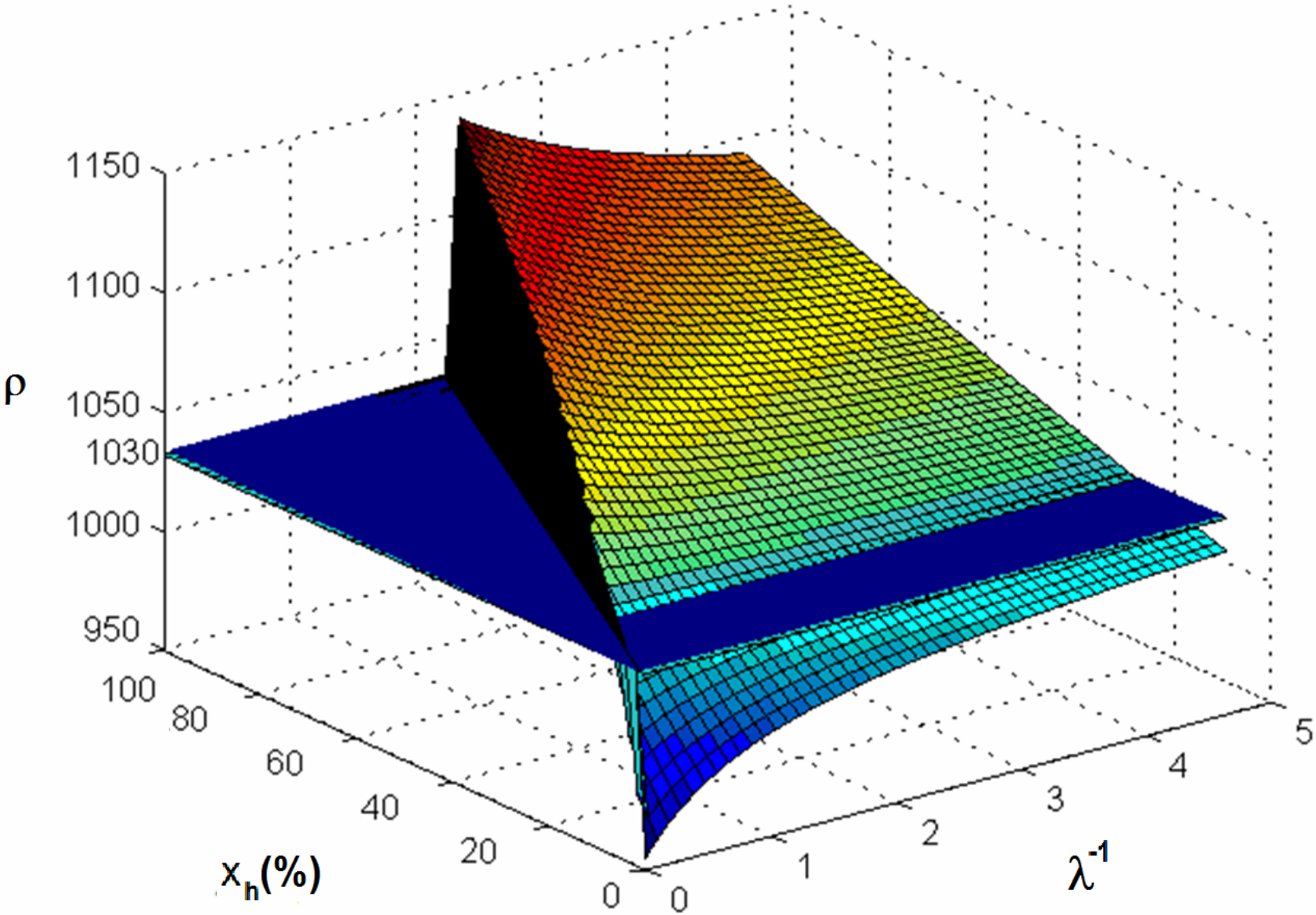
Particle behavior

- Calibrate model particles to ORNL particles
  - sinking rate
  - diameter shrinkage rate



- Composition expressed as hydrate conversion (x_h) and $\lambda = V_c/V_w$
  - assumed constant throughout dissolution

Density of hydrate composite as a function of x_h and λ^{-1}

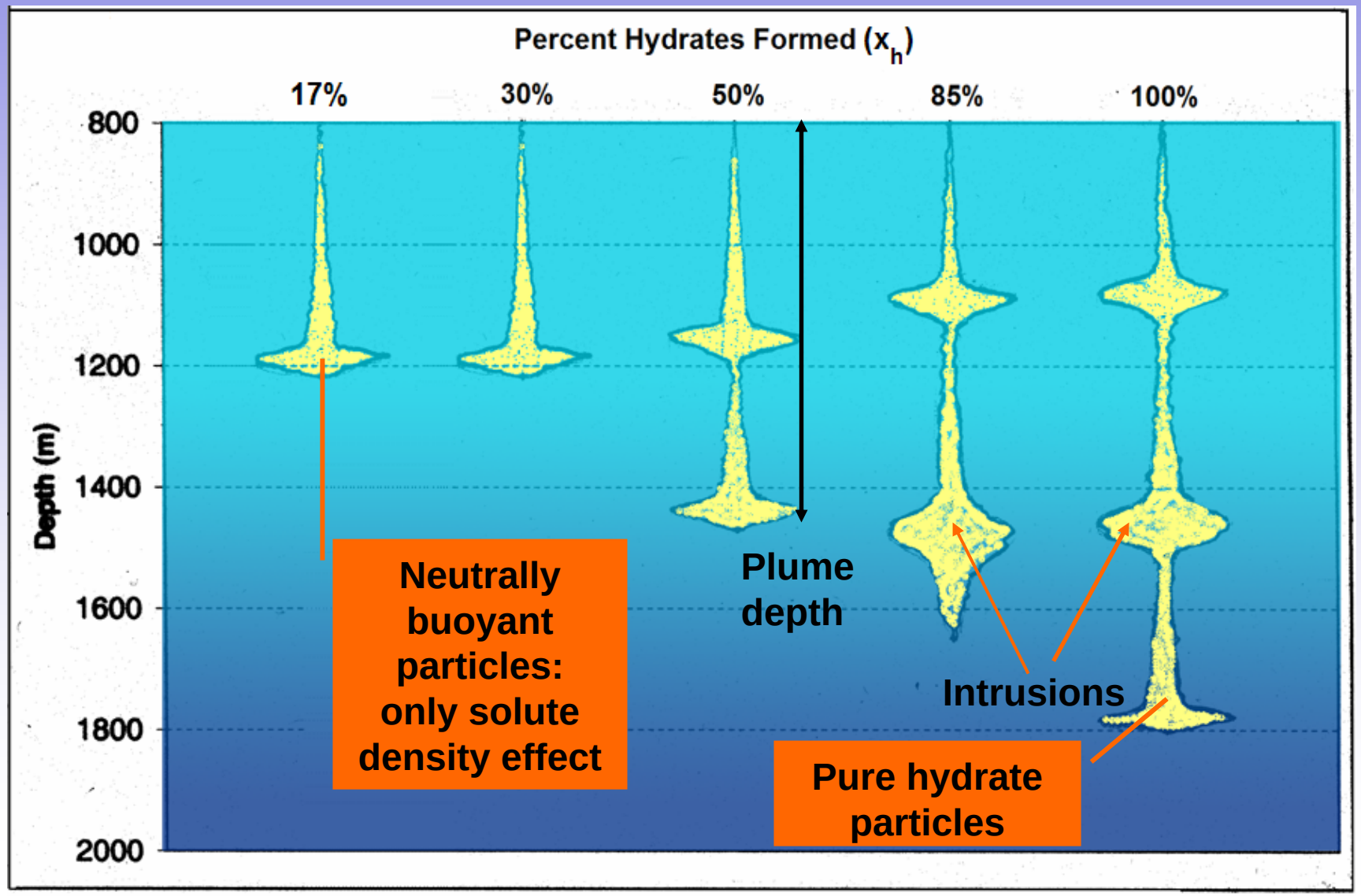


Solute density effect

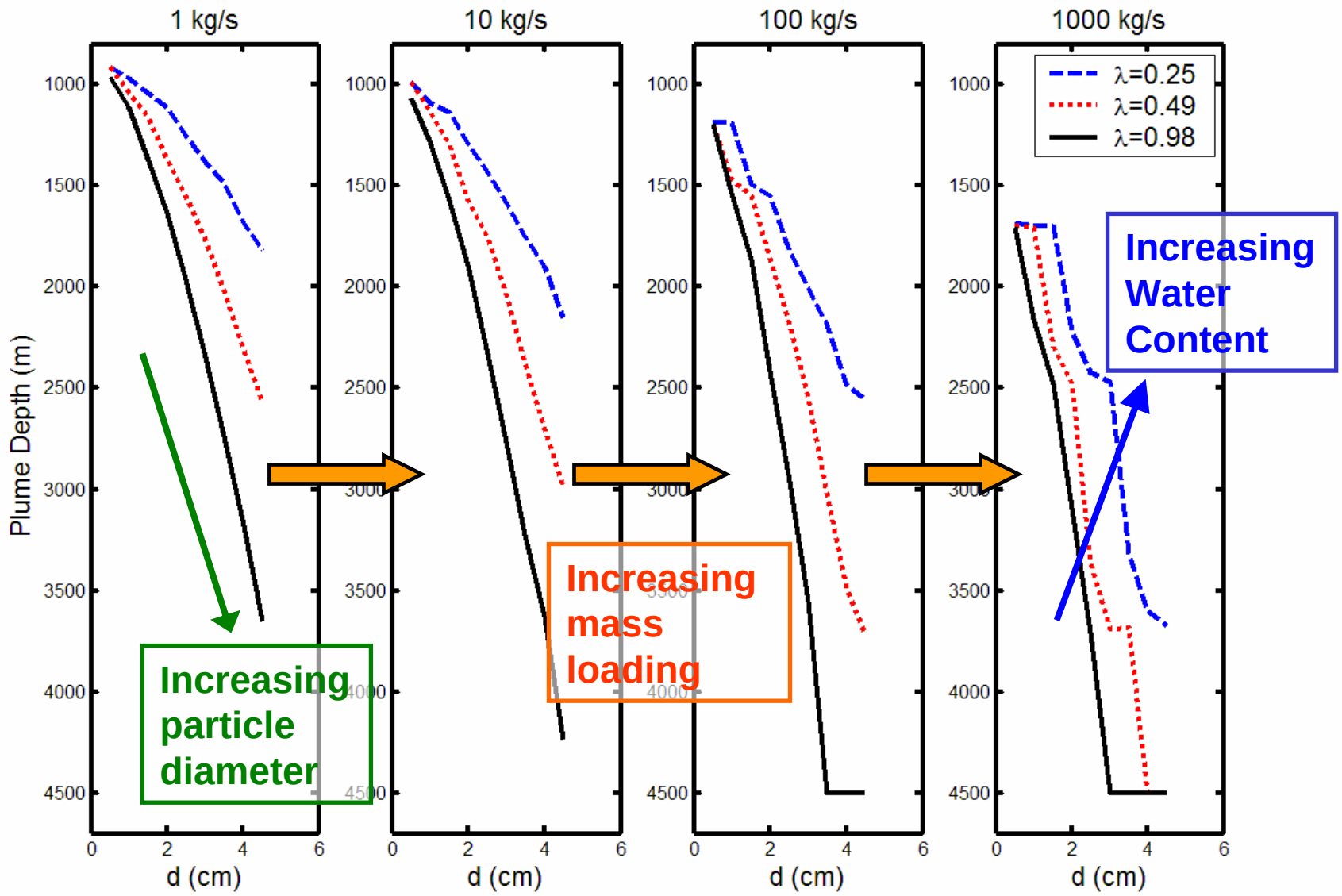
- Dissolved inorganic carbon (DIC) will increase density of ambient seawater, enhance plume sinking
- ‘Two-stage rocket’ with particle dissolution as 2nd stage
- CO_2 disassociation assumed instantaneous in model

Particle plume model

(100 kg/s CO_2, 1 cm diameter spheres, release depth 800 m, $V_c/V_w = \lambda = 0.49$)



Two-phase plume model
(50% reacted hydrate composite spheres)



Field Particle

(Tsouris, Riestenberg, Brewer, Peltzer, Walz)

- Input field particle characteristics into plume model:

Release depth	1200 m
Diameter	0.79 cm
Length	7.0 cm
Sink rate	5.8 cm/s
Shrinkage rate	4.4 μm/s

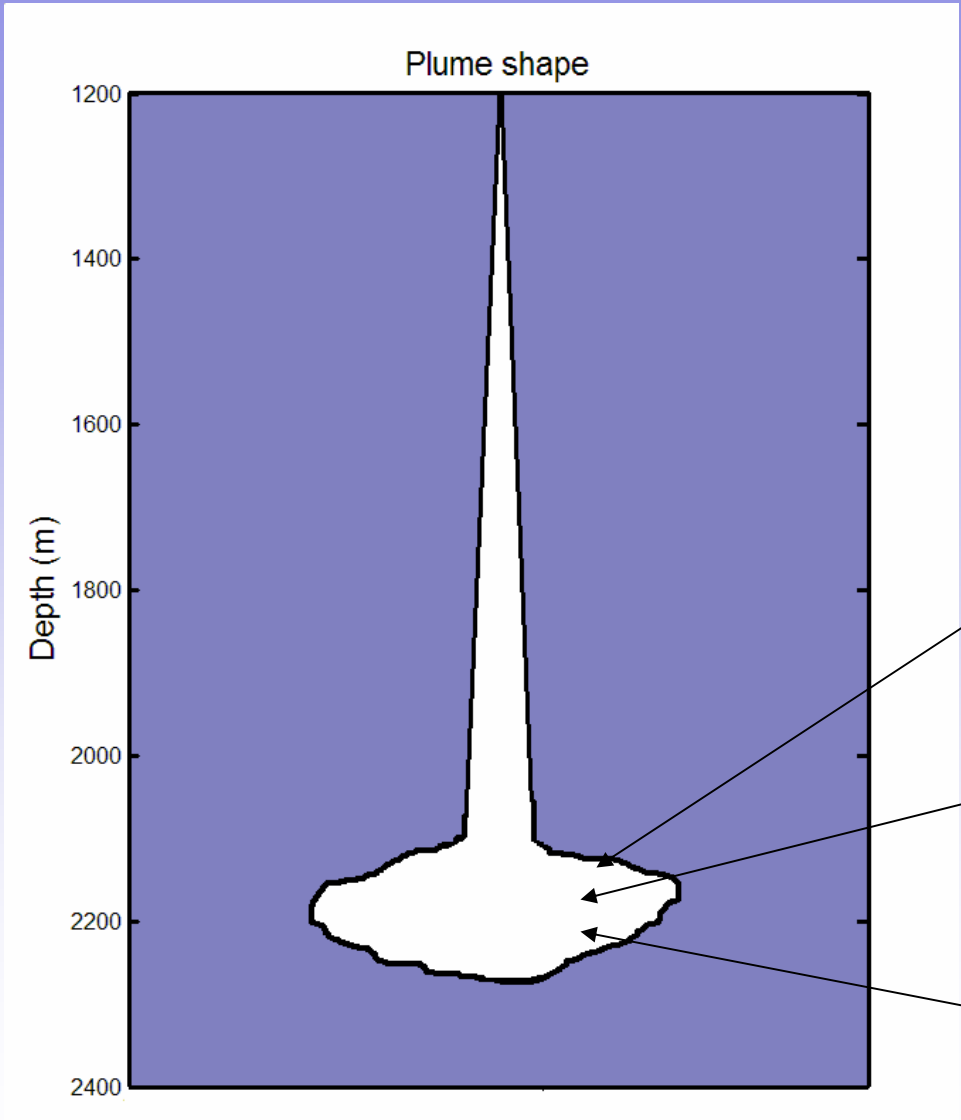
- Model runs:

  CO_2 mass loading of 1, 10, 100, 1000 kg/s of this particle

  (267, 2670, 26700, 267000 particles/s)

- Individual particle predicted to sink and dissolve to about 70 m

Model Results

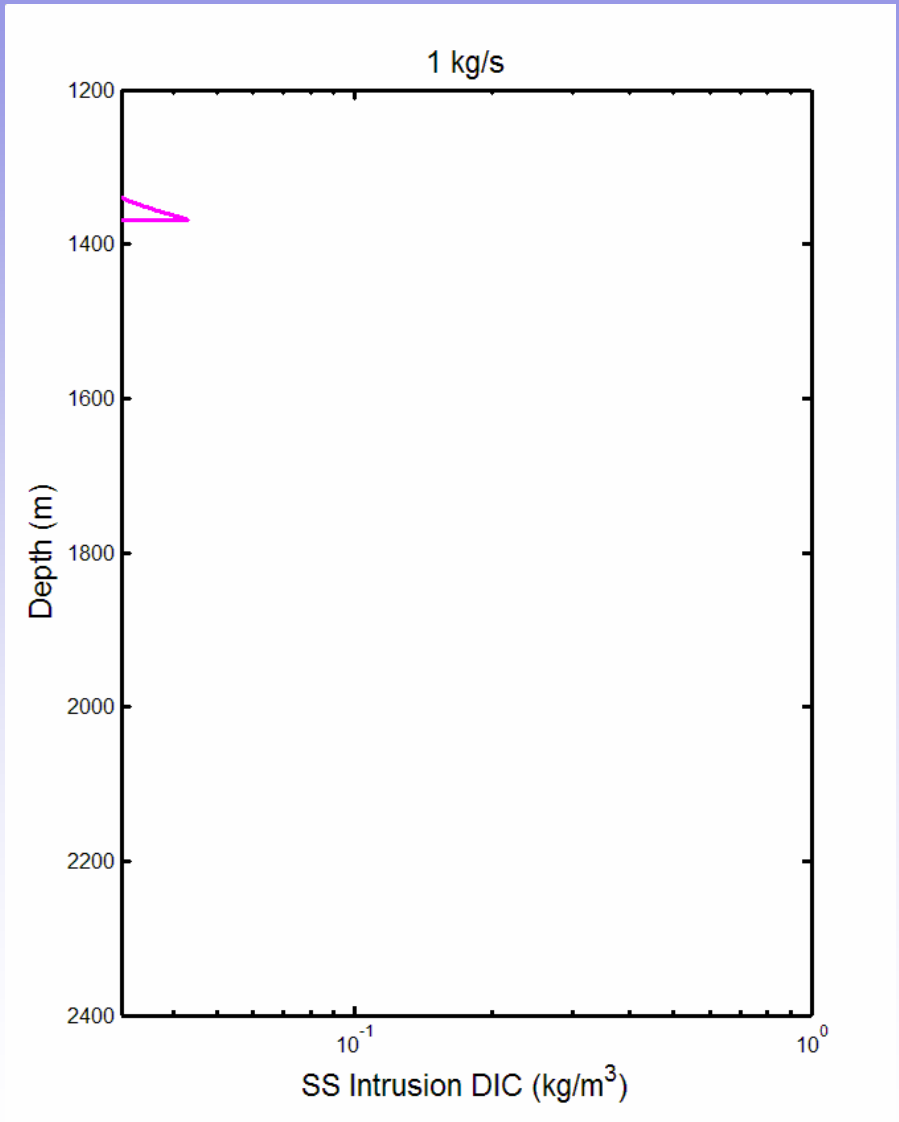


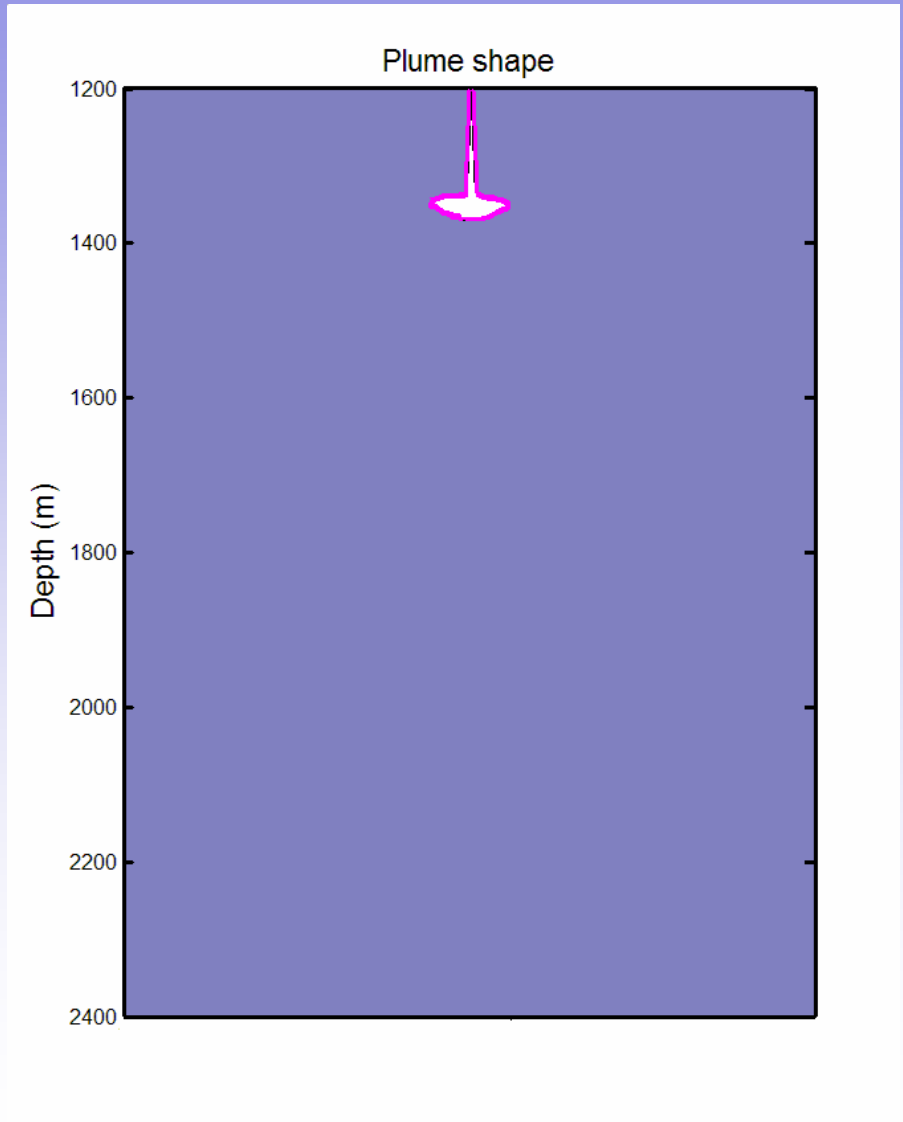
1 peeling event (intrusion) ‘observed’ for all runs

Output: Steady state intrusion DIC, pH drop

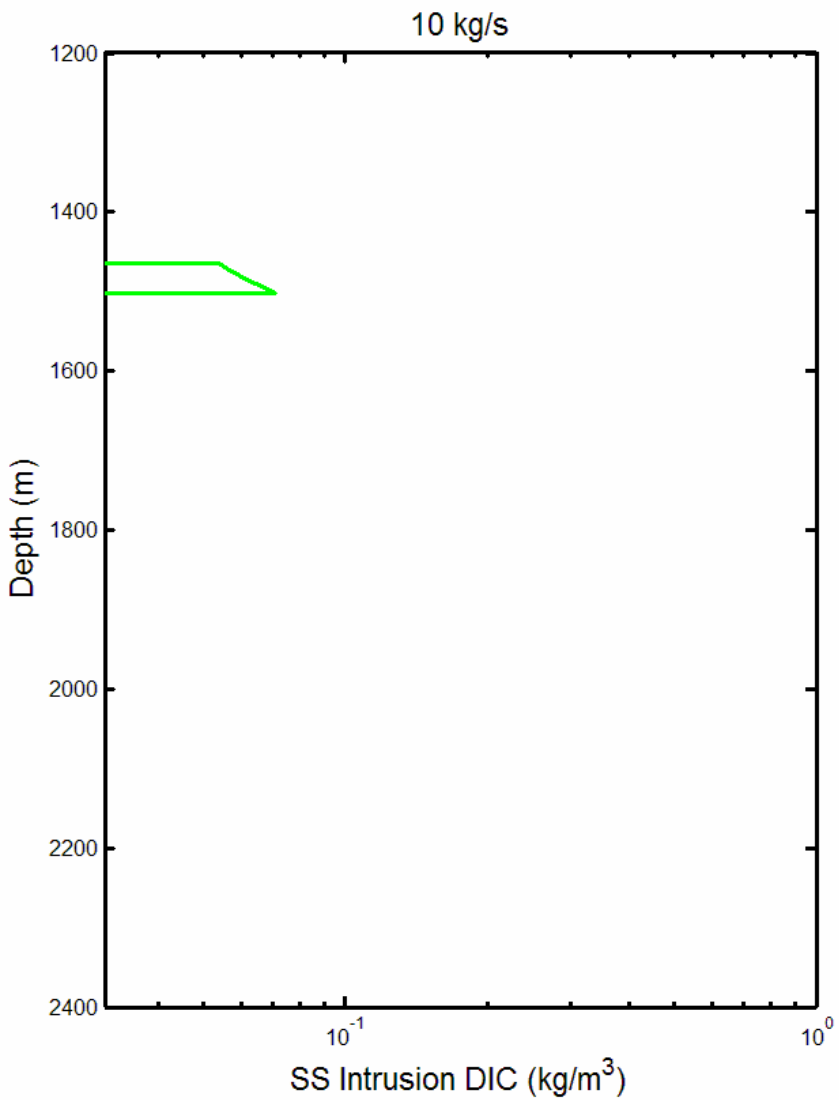
Maximum expected in near field

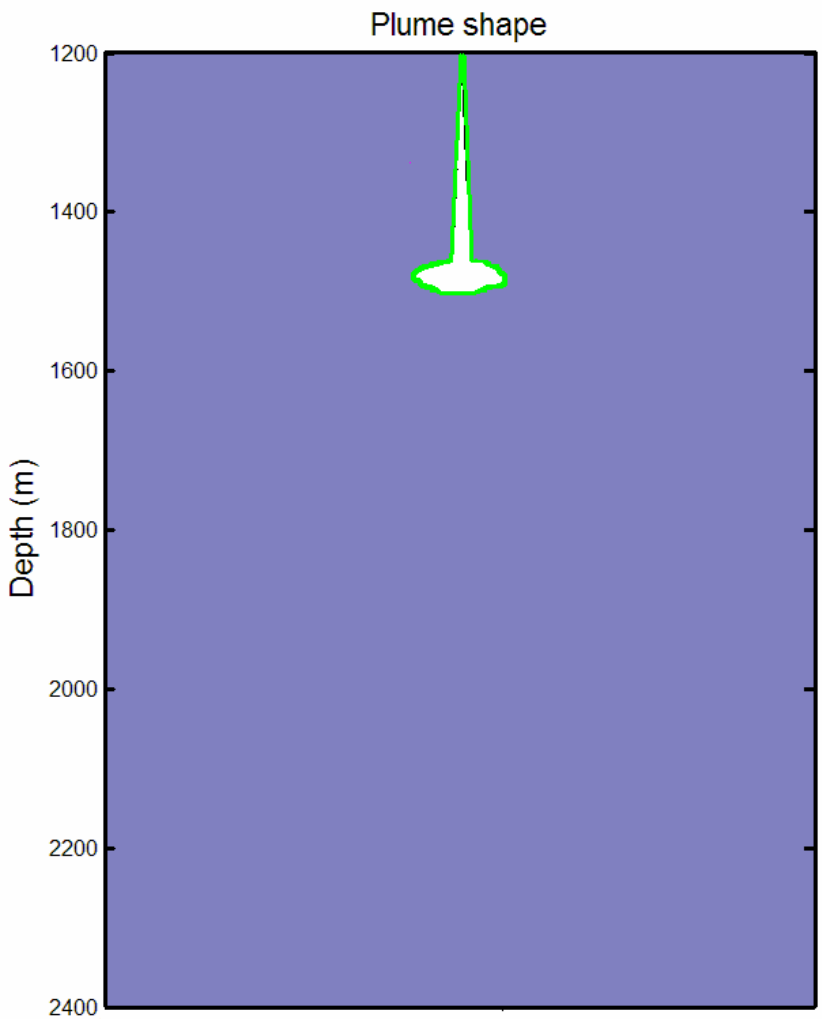
Model Results





Model Results





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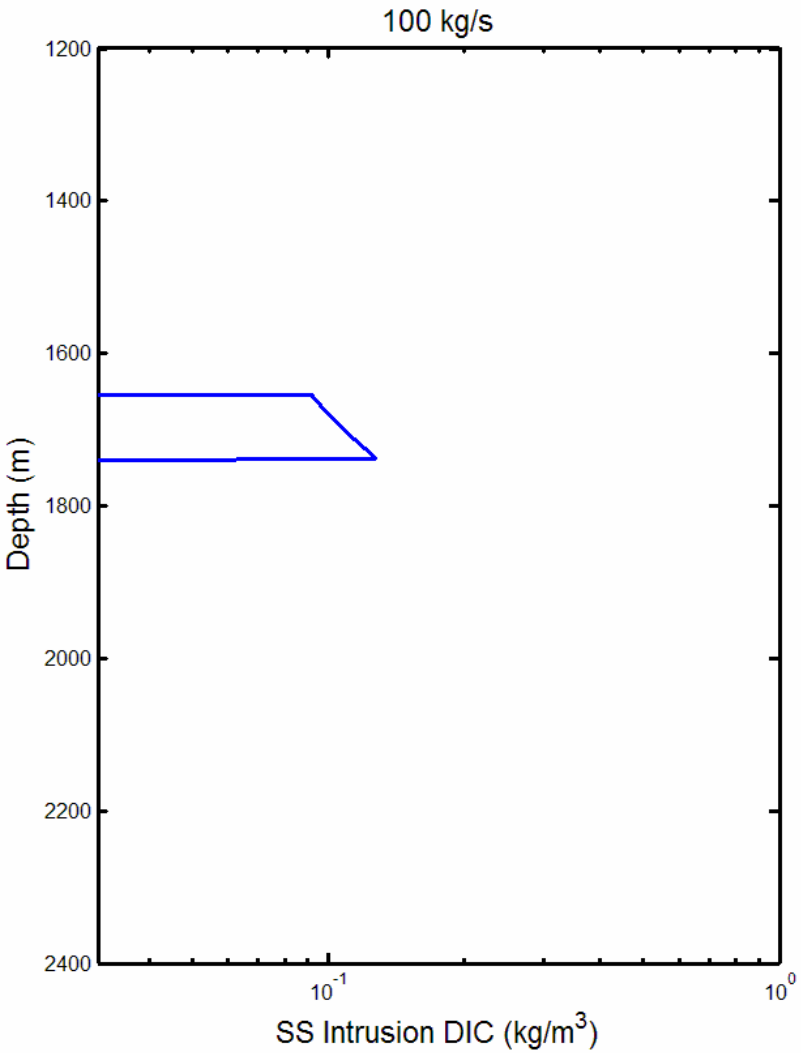

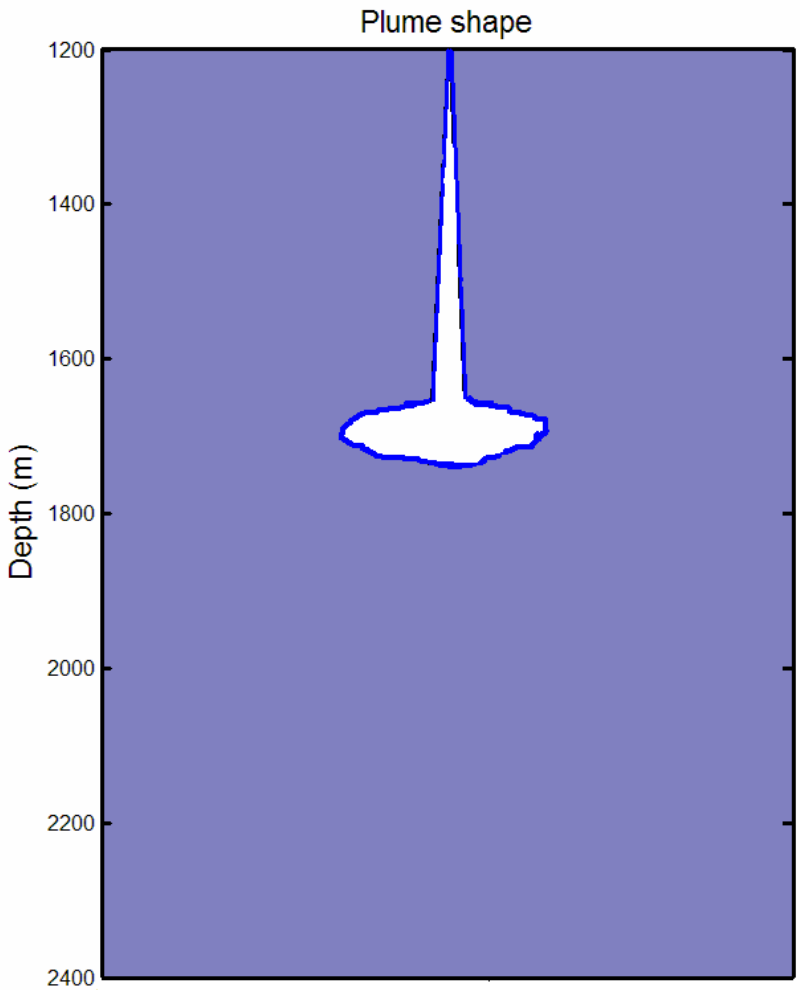

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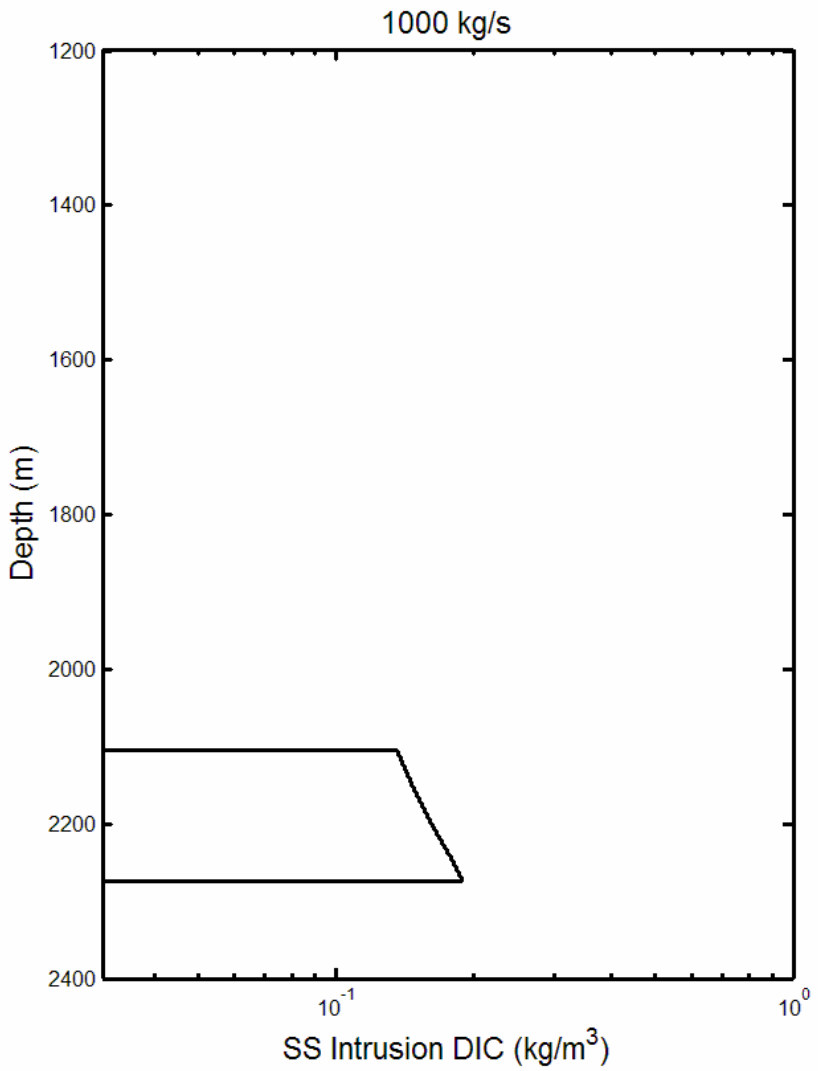
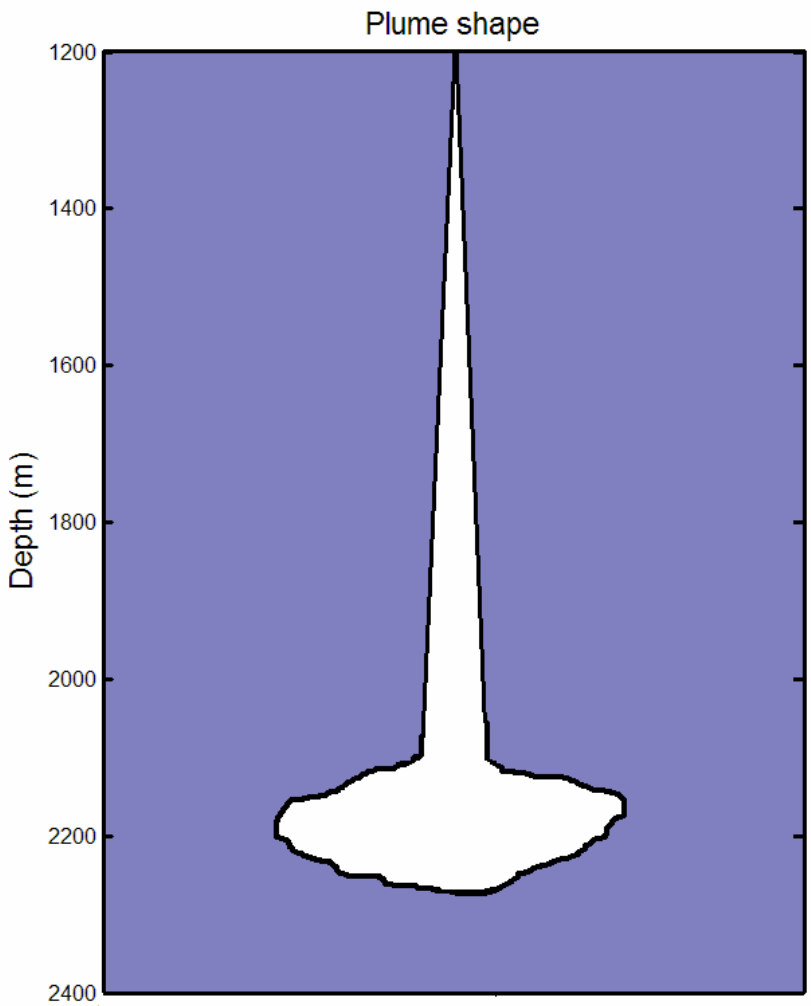
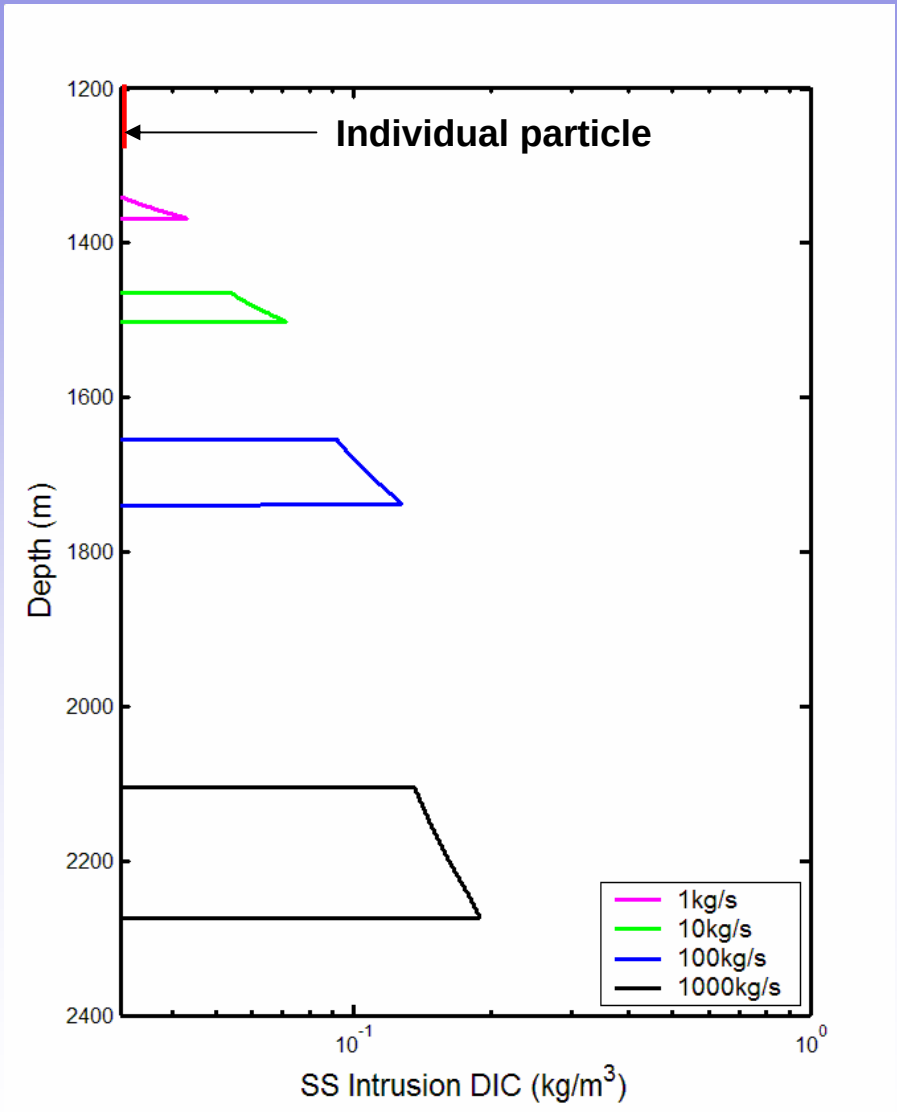




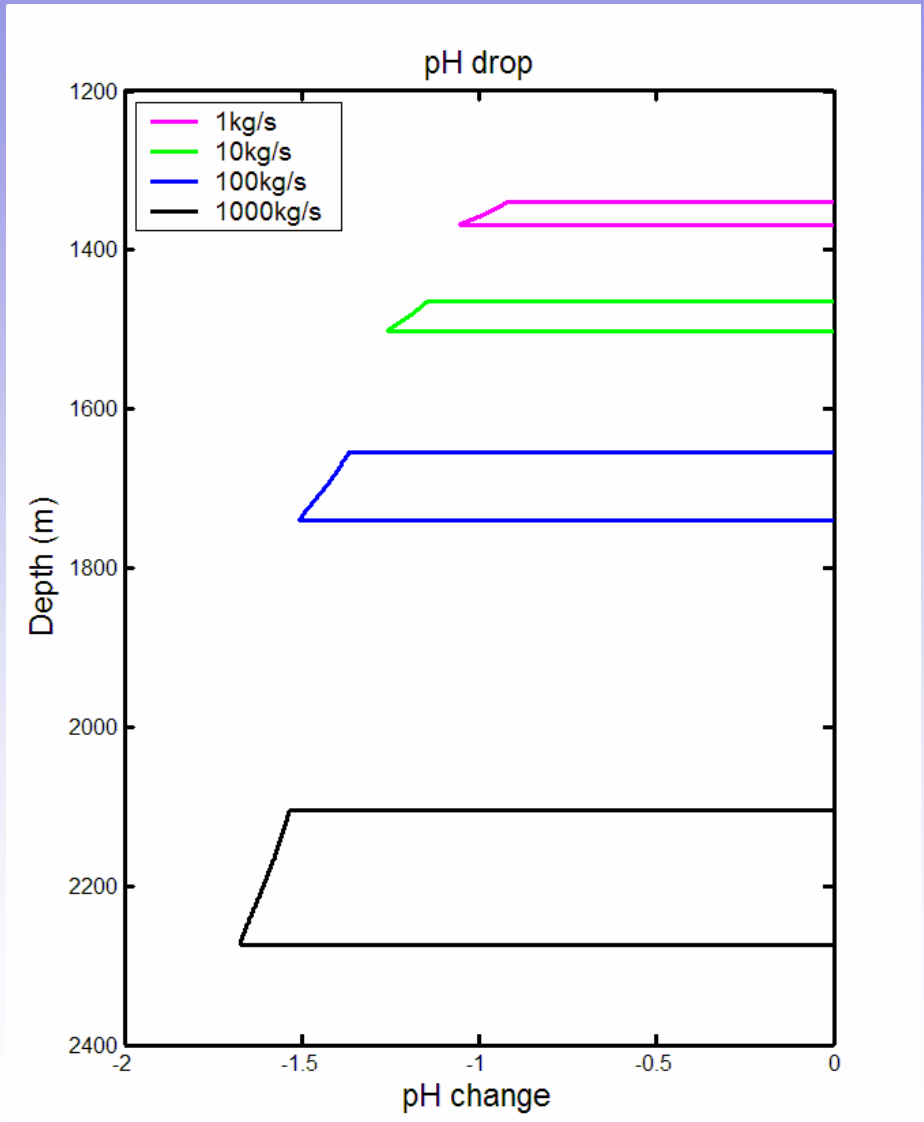
Model results



- Total added DIC in intrusions increases with mass loading
  - Only a fivefold increase with 1000x loading
  - Economy of scale:

  Marginal cost (added DIC) per CO_2 particle sequestered decreases with loading

Model results



- Steady state intrusion pH drop greater for larger mass loading
- Marginal cost (pH drop) per particle decreases with higher mass loading

Conclusions

- Particle plumes sink further than individual particles
  - Solute density effect
  - Plume effect

- How to further increase plume sinking
  - Increase hydrate conversion
  - Reduce unreacted water in particle
  - Increase particle size / reduce particle breakup
  - Increase mass loading

Acknowledgements

- MIT:
  - Eric Adams, Peter Israelsson, Scott Socolofsky, Brian Crounse, Eric Wannamaker
- ORNL:
  - Costas Tsouris, David Riestenberg
- MBARI:
  - Peter Brewer, Edward Peltzer, Peter Walz

Field studies (ORNL)

(Tsouris, Riestenberg, Brewer, Peltzer, Walz)

ORNL particles	2004 Larger injector		2002 Smaller injector		
particle name	2004(1)	2004(2)	2002(1)	2002(2)	2002(3)
release depth (m)	1200	1000	1100	1226	1300
behavior	sink	sink	float	sink	neutral
diameter (cm)	0.79	0.79	0.60	0.61	0.57
length (cm)	7.0	6.5	2.5	3.4	2.6
sinking rate (cm/s)	5.8	5.2	-6.0	2.0	0
shrink rate (μm/sec)	4.4	6.6	5.3	7.4	4.1
est. conversion (%)	55	47	0	22	16

Next: model this particle

Released at 1 kg/s – 1000 kg/s

MBARI particles	2004 Larger Injector		2002 Smaller injector		
behavior	sink	sink	float	sink	neutral
diameter (cm)	0.79	0.79	0.60	0.61	0.57
length (cm)	7.0	6.5	2.5	3.4	2.6
sinking rate (cm/s)	5.8	5.2	-6.0	2.0	0
shrink rate (μm/sec)	4.4	6.6	5.3	7.4	4.1
Using cylindrical drag coefficient model:					
ρ (g/cm^3)	1.05(7)	1.05(1)	0.99(8)	1.03(7)	1.03(4)
Estimated x_h (%)	55	47	0	22	16
Range x_h (varying λ, ρ_h)	41-65	39-55	0-2	20-26	15-19

Behavior of large scale releases of these particles?

MBARI particles	2004 Larger injector		2002 Smaller Injector		
behavior	sink	sink	float	sink	neutral
sinking rate (cm/s)	5.8	5.2	-6.0	2.0	0
shrink rate (μm/sec)	4.4	6.6	5.3	7.4	4.1
ρ_p (g/cm^3)	1.05(7)	1.05(1)	0.99(8)	1.03(7)	1.03(4)
X_h (%)	55	47	0	22	16
Sinking depth (m) for					
Individual particle	69	41	-	10	-
1 kg/s CO2 release	169	126	-	123	80*
10 kg/s	303	229	-	223	152*
100 kg/s	540	496	-	486	327*
1000 kg/s	1074	979	-	961	634*

*Estimate for neutrally buoyant particle

Field studies

	2004 Injections Larger nozzle		2002 Injections Smaller nozzle		
release depth (m)	**1200**	**1000**	**1100**	**1226**	**1300**
Additional DIC (kg/m3) (Average pH change)					
Individual particle	**-**	**-**	**-**	**-**	**-**
1 kg/s CO2 release	**0.04 (-1.0)**	**0.07 (-1.2)**	**-**	**0.07 (-1.2)**	**0.22* (-1.7)***
10 kg/s	**0.07 (-1.2)**	**0.11 (-1.5)**	**-**	**0.11 (-1.45)**	**0.34* (-1.9)***
100 kg/s	**0.12 (-1.5)**	**0.15 (-1.6)**	**-**	**0.15 (-1.6)**	**0.46* (-2.1)***
1000 kg/s	**0.18 (-1.7)**	**0.21 (-1.7)**	**-**	**0.22 (-1.7)**	**0.74* (-2.3)***

*Estimate for neutrally buoyant particle