3-D Simulations of the Cold, Thin Atmospheres of Triton and Pluto

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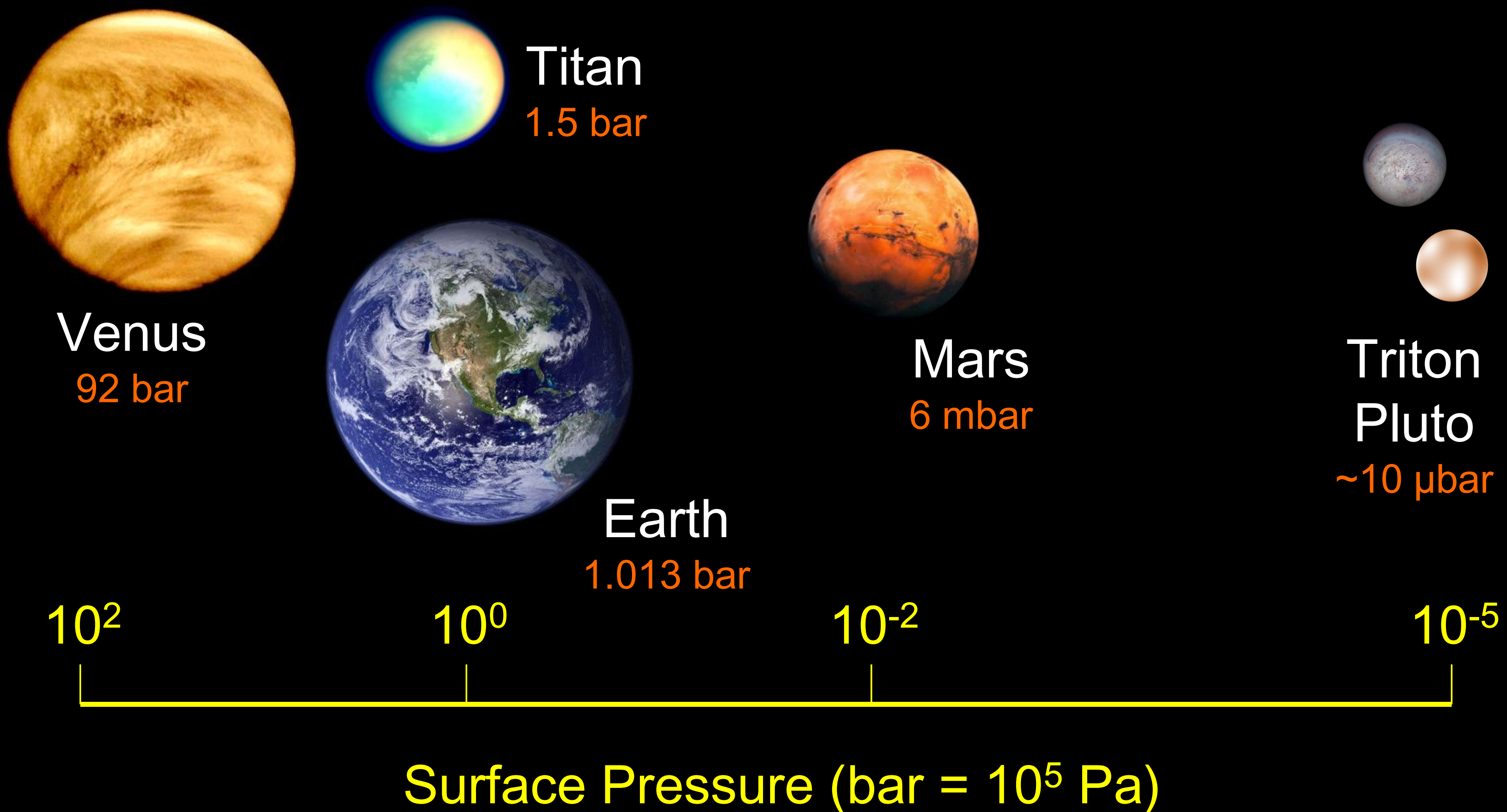
Outline

- The atmospheres of Triton and Pluto
- Applying the Ames General Circulation Model
- Initial Results
  - N_2 ice covered globe
  - Exposed southern pole
- Future work

Atmospheres of “Terrestrial” Solar System Bodies



Triton & Pluto

- Both are likely Kuiper Belt Objects
  - Density: 2.0 g/cm^3
  - Radius: Triton = 1353 km, Pluto = 1152 $\pm$ 32 km
  - Rotation Rate: Triton = 5.877 day, Pluto = 6.387 day
  - Distance from Sun: Triton = 30.1 AU, Pluto = 31.9 AU
  - Surface Gravity: Triton = 0.78 m/s^2, Pluto = 0.65 m/s^2
- Similar Atmospheres
  - Mostly (> 99% N_2), trace CH_4, CO
  - Surface pressure of 8-24 microbars (0.8 - 2.4 Pa)

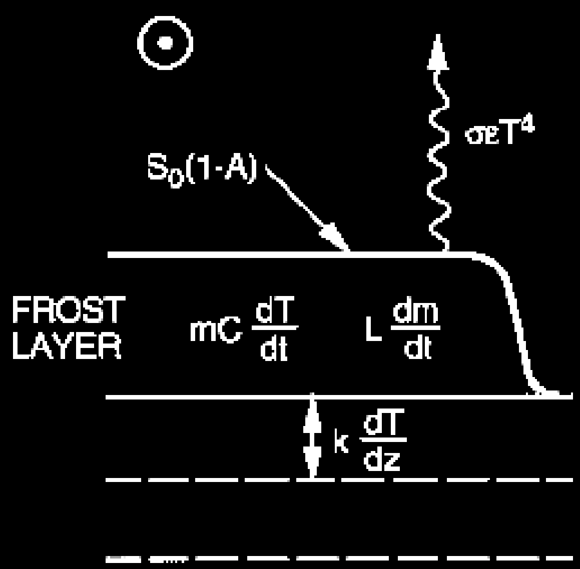
Motivation

- Unique type of atmosphere
  - Latent heat on order of solar insolation
  - No dynamical (GCM) atmosphere simulation reported in the literature
- Likely other KBOs have similar atmospheres
- Pushes the limits of General Circulation Models
- New Horizons due at Pluto July 2015

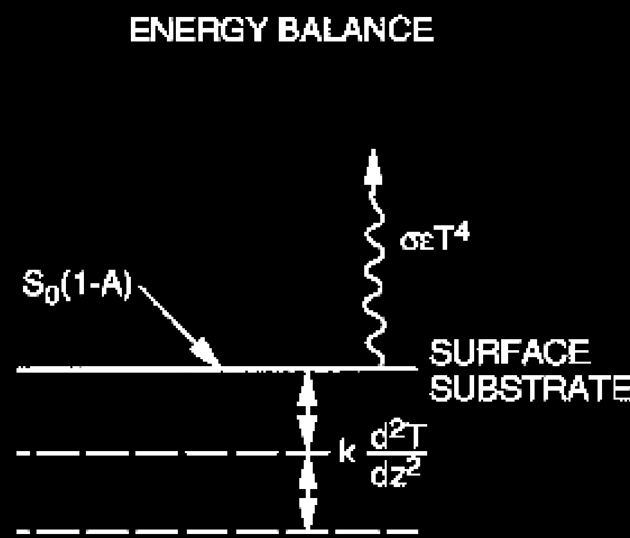
Energy Balance

- Solar insolation = 1.5 W/m^2
- Latent heat N_2
  - L = 250,000 J/kg (vapor - β-phase transition)

$$m_f C_p \frac{dT}{dt} = S_0(1-A) - \varepsilon\sigma T^4 + L\frac{dm}{dt} + k\frac{dT}{dz}$$



Ice covered (Mass balance)



Bare substrate

Hansen & Paige, 1996

Vapor Pressure Equilibrium

- Antoine equation relates surface vapor pressure to bulk temperature of surface ice

For N_2 @ T= 63 -126° K

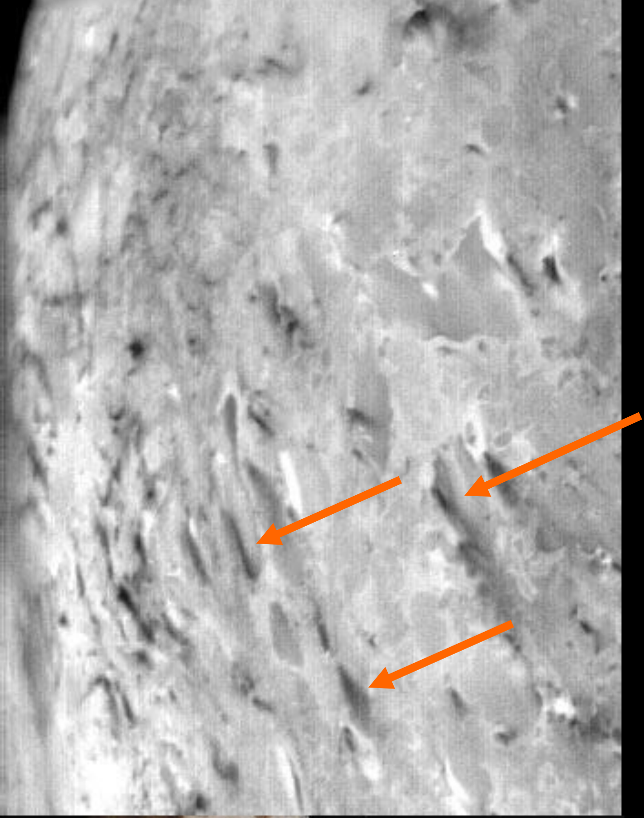
A = 3.7362

B = 264.651

C = -6.788

N_2 Frost Temperature	N_2 Surface Pressure
50° K	4.1 mbar
45° K	650 µbar
42° K	166 µbar
41° K	100 µbar
38° K	18 µbar
34° K	1 µbar

Triton’s Winds



- Active nitrogen geysers photographed by Voyager 2 between -37º and -62º latitude
- Active geysers rise to 8 km, then are sheared laterally
- Winds in mid-southern latitudes from 1 to 3 km altitude move east at 5-15 m/s
- Winds move westward at 8 km at 19 m/s

Ames GCM Features

- Numerically solves hydrodynamic equations governing 3-D gas flow
- Models thermodynamics of gas condensation and sublimation of main constituent gas (CO_2 for Mars) including heat flow into/out of substrate
- Solves radiative transfer equations for the main atmospheric gas
- Calculates solar insolation per grid per time step given rotational, orbital motion
- Provides for input for subsurface thermal profile per grid point
- Allows input of a surface albedo map

Changes to Ames GCM

- Input Triton physical, rotational, and orbital parameters around the time of the Voyager 2 encounter
- Convert vapor pressure equilibrium equations from CO_2 to N_2 (Antoine equation)
- Select appropriate values for N_2 frost emissivity, surface and N_2 frost albedo, substrate thermal inertia, and N_2 mass inventory (Hansen and Paige, 1992)
- Disable CO_2 based radiative transfer code
- Define initial subsurface thermal profile

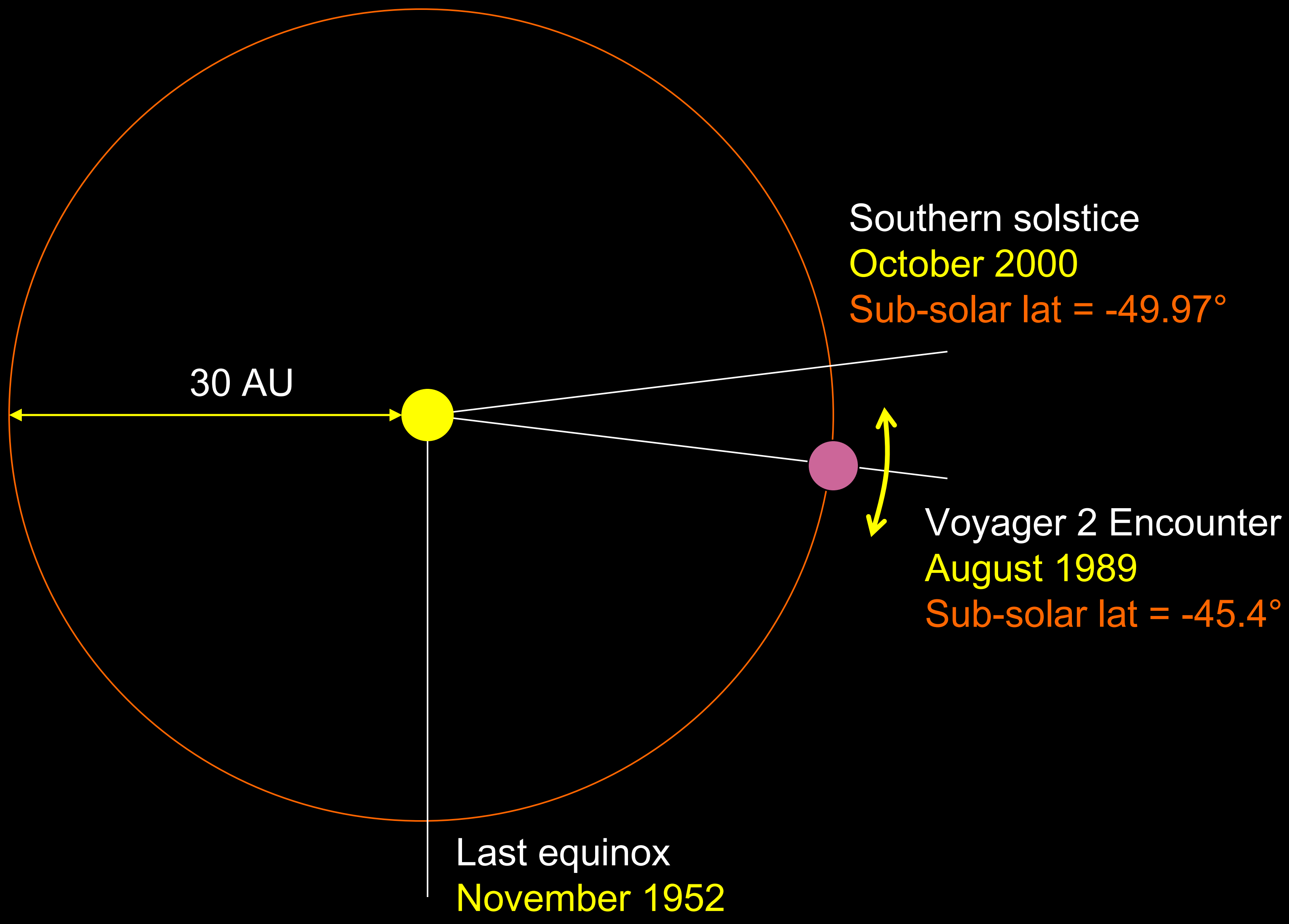
Simulation Conditions

Physical & Orbital Parameters	
Semi-major axis	30.07 AU
Radius	1352 km
Surface gravity	0.78 m/s^2
Rotation rate	5.877 day
Sub-solar latitude at solstice	+/- 50.4°
Sub-solar latitude at time of simulation (Ls = 258.5)	- 48°

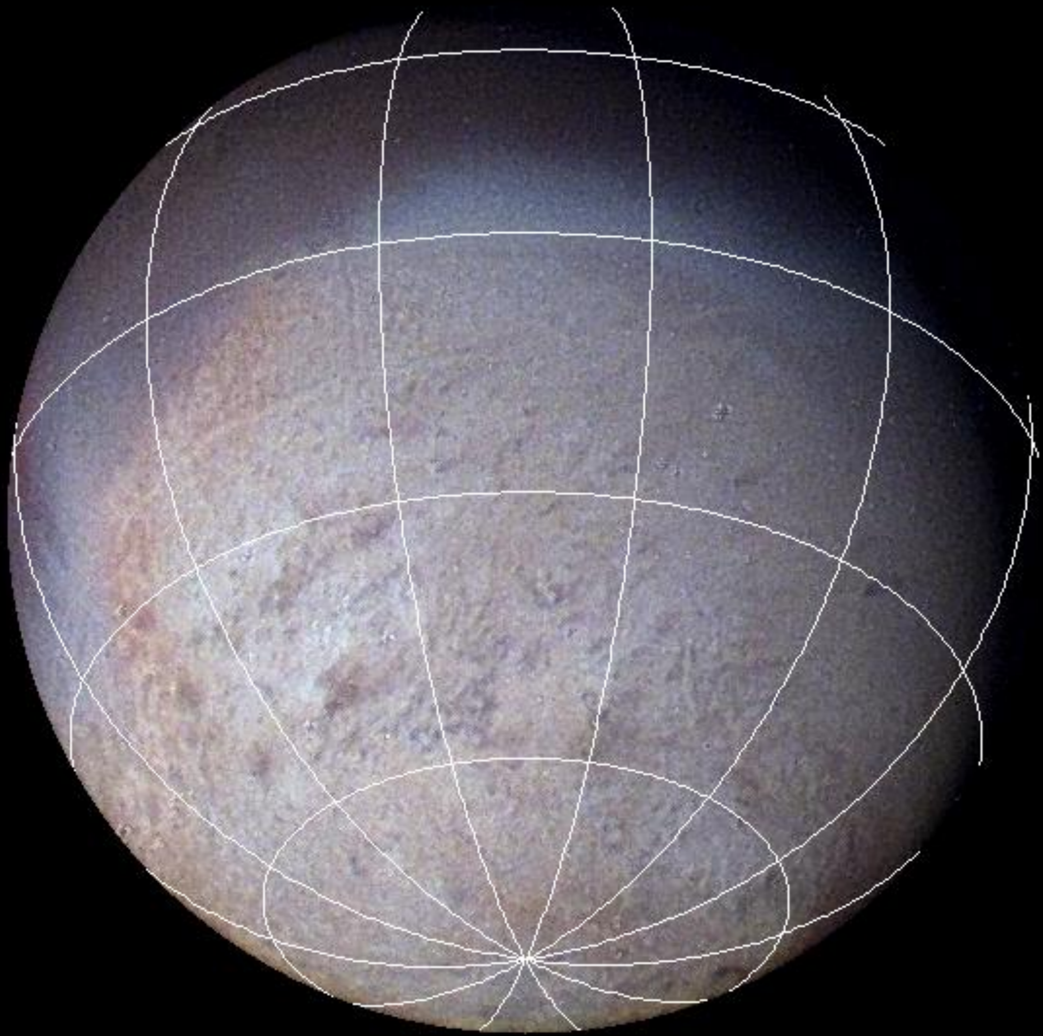
N_2 Constants & Initial Values	
N_2 R_{gas}	296.6 J/kg K
N_2 Cp	1039 J/kg K
N_2 ß-ice latent heat	250,000 J/kg
Initial N_2 surface ice inventory	100 kg/m^2
Initial surface pressure	10 µbar

Thermal Balance Parameters	
N_2 frost albedo	0.62
N_2 ice emissivity	1.0
Substrate albedo	0.8
Substrate thermal inertia	292.9 J/m^2 K $s^{0.5}$

Triton Simulation Window



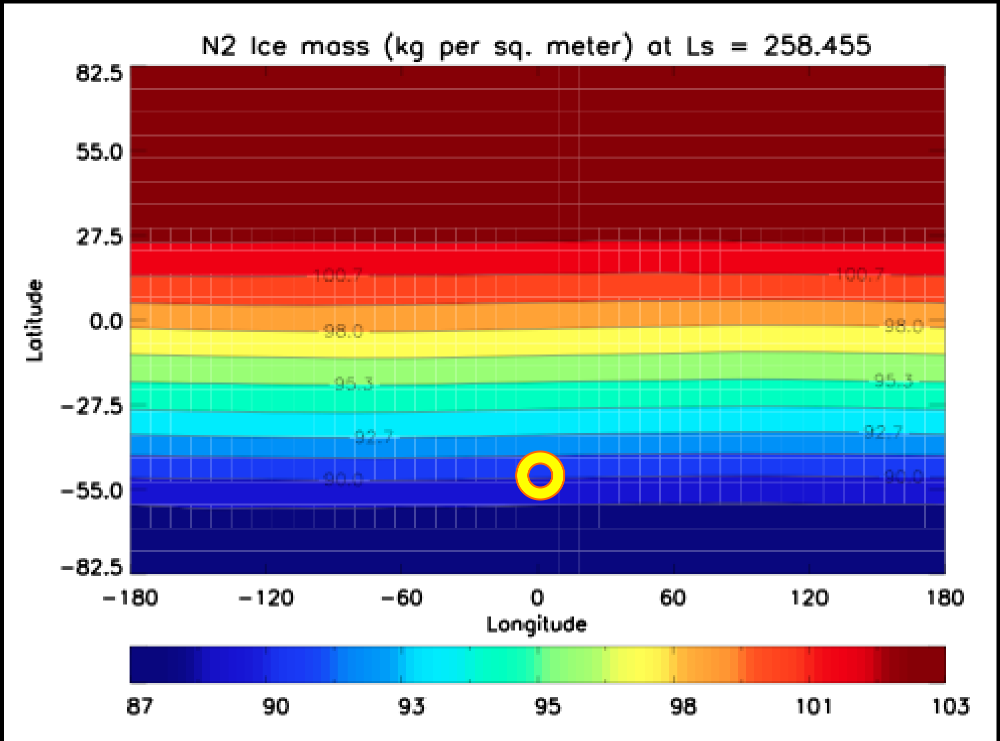
Triton Simulation Orientation



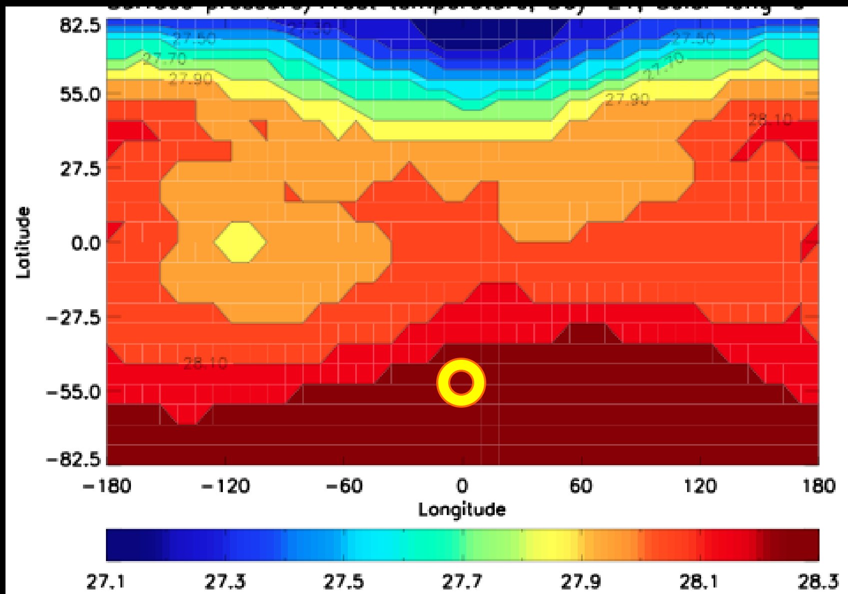
- Run at Ls = 258 (Southern summer solstice = 270)
- Sub-solar latitude is -48º
- No insolation above +42º

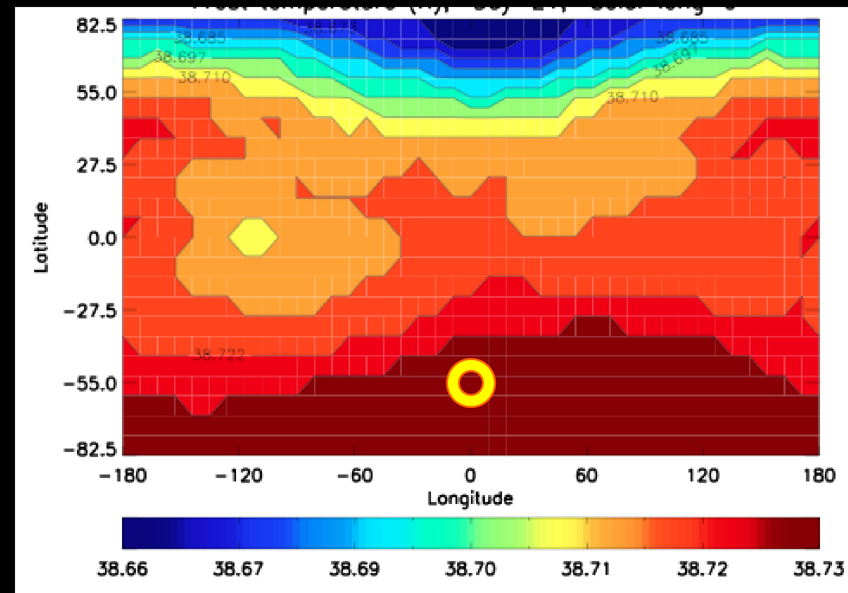
Condensation Flow Simulation

- Start with 100 kg/m^2 N_2 ice
- Start with initial surface pressure of 10 μbar
- Run for 20 Triton days (117 Earth days)
- Still ice covered at the illuminated pole



Surface Temperature & Pressure





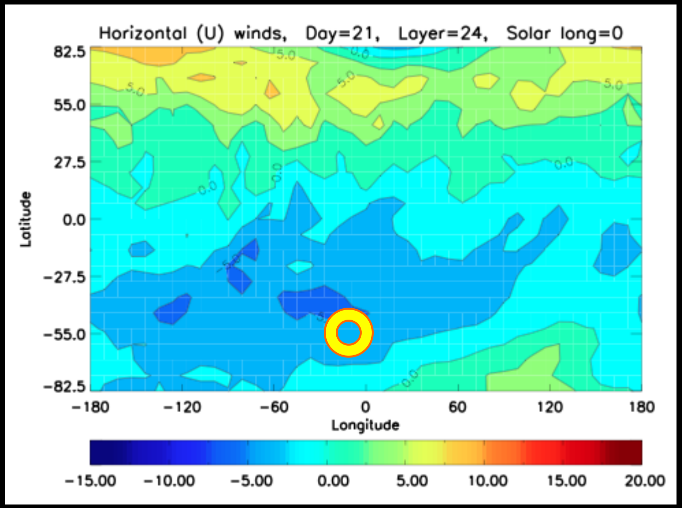
Surface Pressure (microbars)

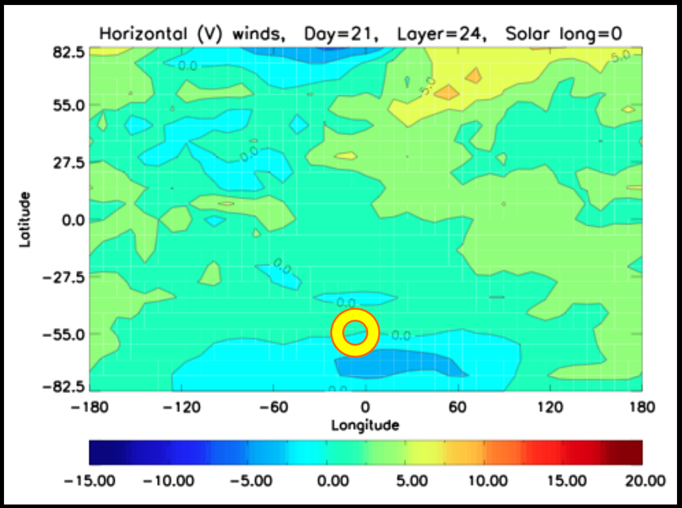
Surface Temperature (K)

$\Delta P_{\text{pole to pole}} = 1.2\ \mu\text{bar}$

$\Delta T_{\text{pole to pole}} = 0.07\ \text{K}$

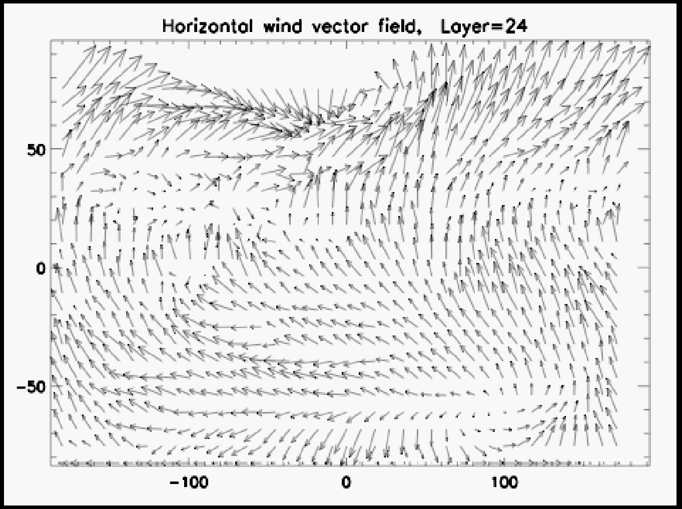
Surface winds (15 m)





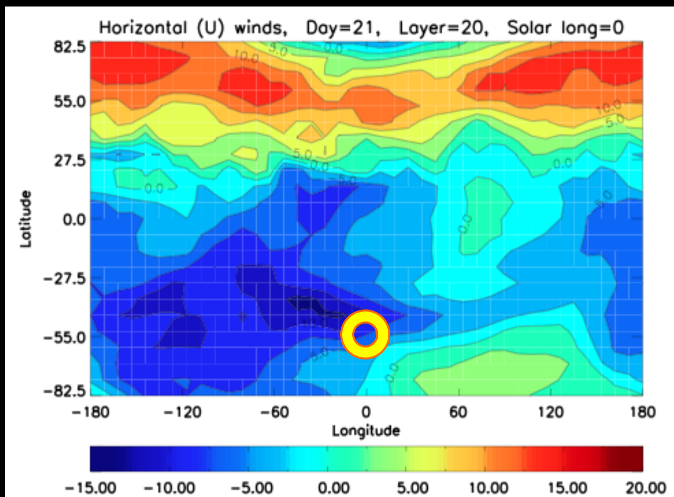
V (North-South) Winds

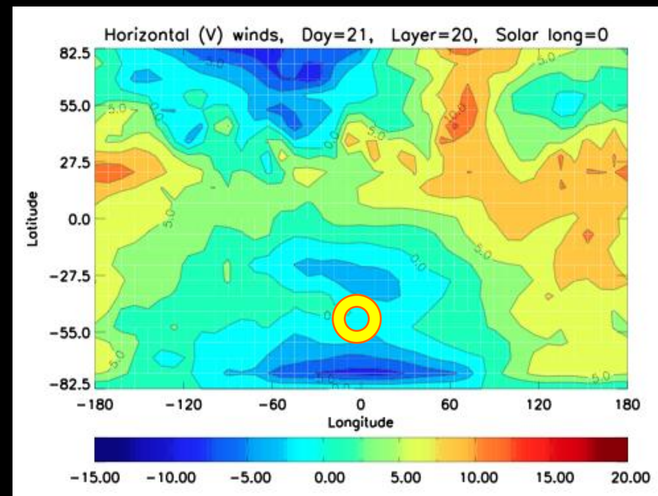
U (East-West) Winds



U-V Wind Vector Field

Winds at 1 km





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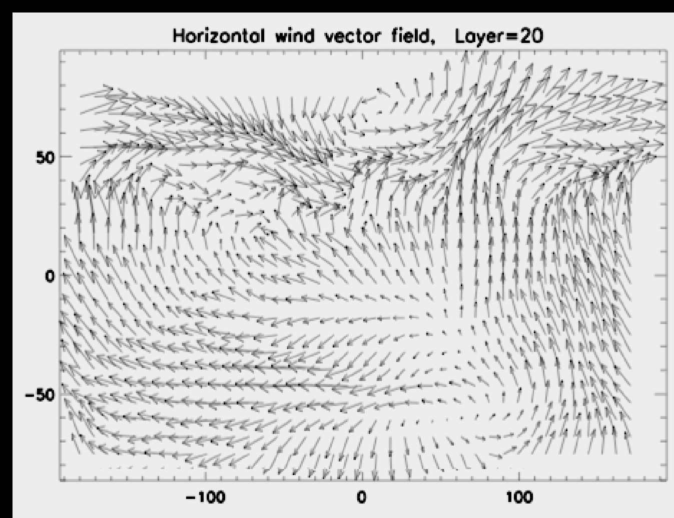
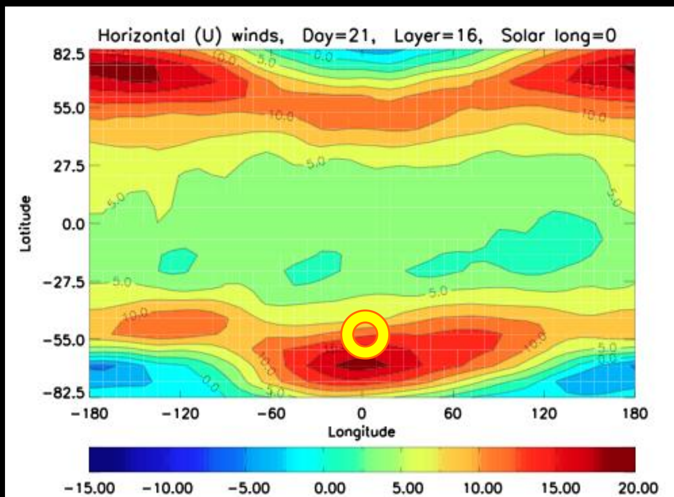
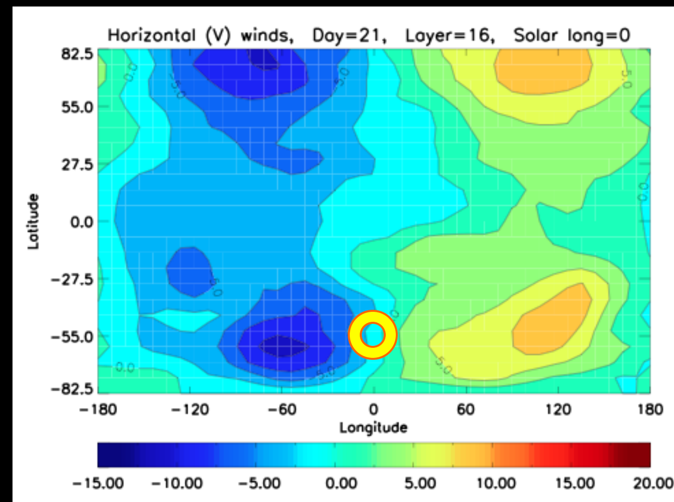


U-V Wind Vector Field

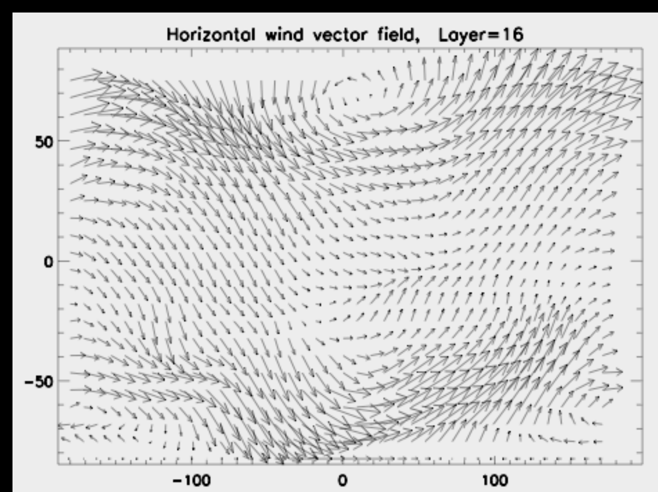
Winds at 8 km





V (North-South) Winds

U (East-West) Winds



U-V Wind Vector Field

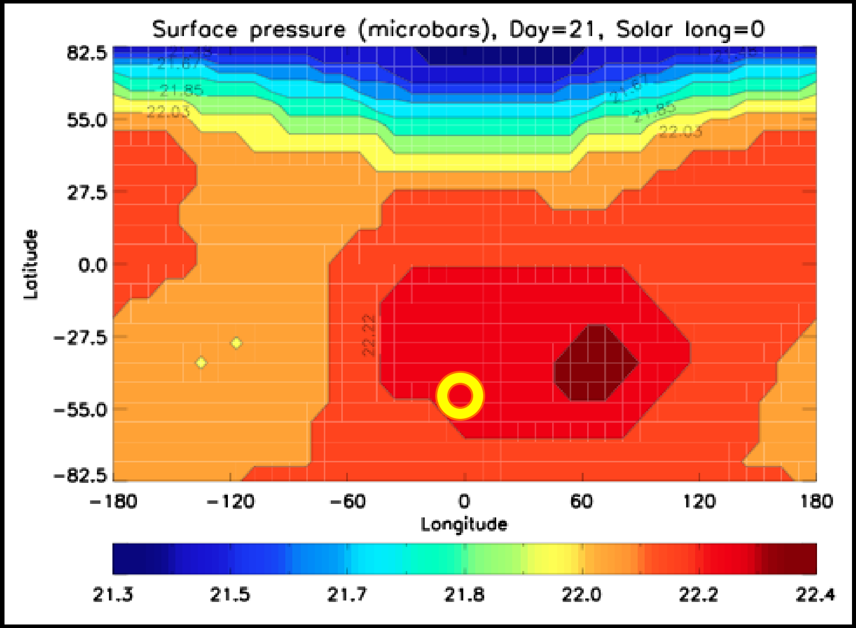
Simulation Results

- Ames GCM running at Triton/Pluto conditions
  - Tens of microbars
  - Temperatures of 35-40 K
  - N2 atmosphere

- Condensation flow winds
  - Order of 1-20 m/s
  - Agrees with Voyager 2 observations

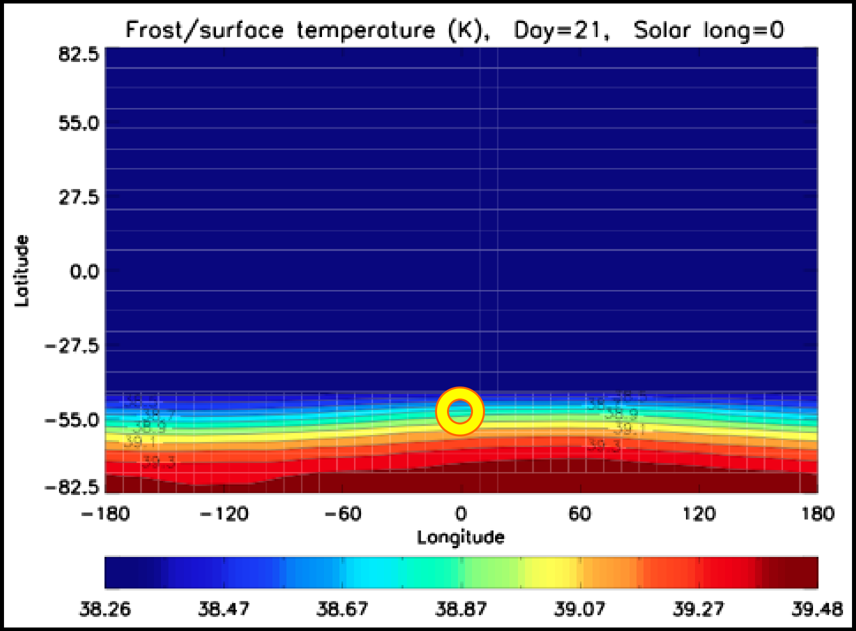
Exposed South Pole Results (Day 21)

- Start with 10 kg/m^2 N_2 ice
- South pole N_2 ice totally sublimes away



Surface Pressure (µbar)

$\Delta P_{\text{pole to pole}} = 1.1\ \mu\text{bar}$

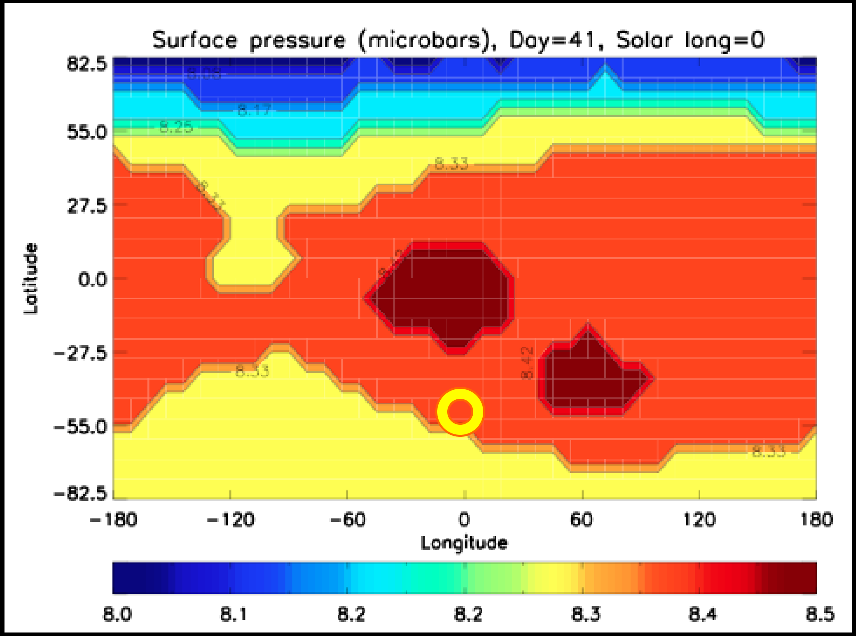


Surface Temperature (K)

$\Delta T_{\text{pole to pole}} = 1.22\ K$

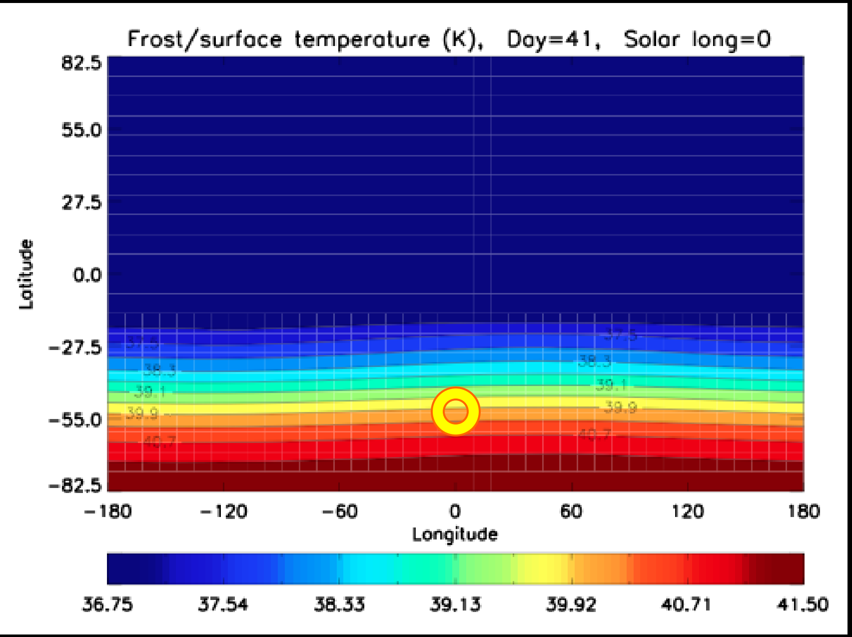
Exposed South Pole Results (Day 41)

- Surface pressure down to 8 μbar after 40 days
- Runaway condensation



Surface Pressure (μbar)

$\Delta P_{\text{pole to pole}}$ = 0.5 μbar



Surface Temperature (K)

$\Delta T_{\text{pole to pole}}$ = 4.75 K

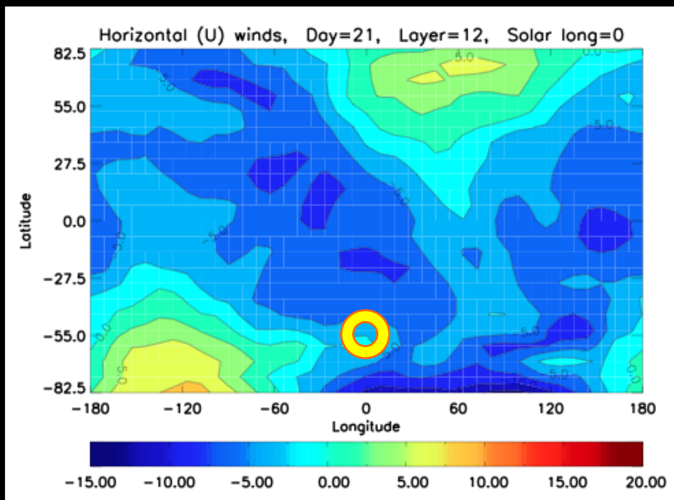
Future Work

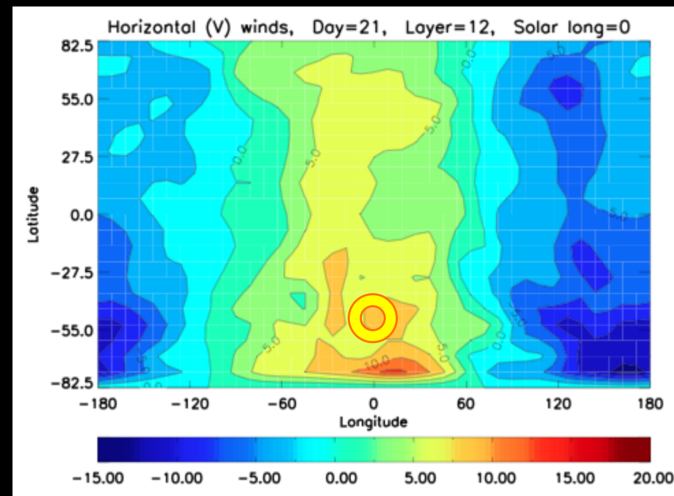
- Regulate thermal balance to prevent runaway sublimation/condensation
- Force observed vertical pressure-temperature profile
  - Upper atmosphere heat flux + conduction
  - Newtonian cooling scheme
  - Radiative transfer with CH_4 and CO
- Run longer simulations

Thank You

Bonus Slides

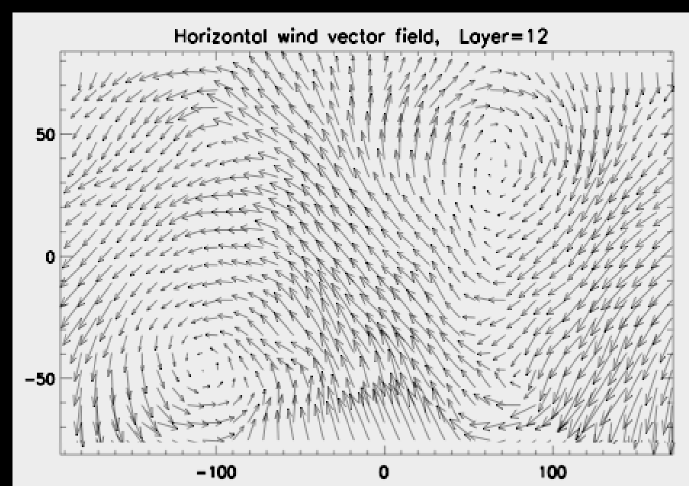
Winds at 39 km





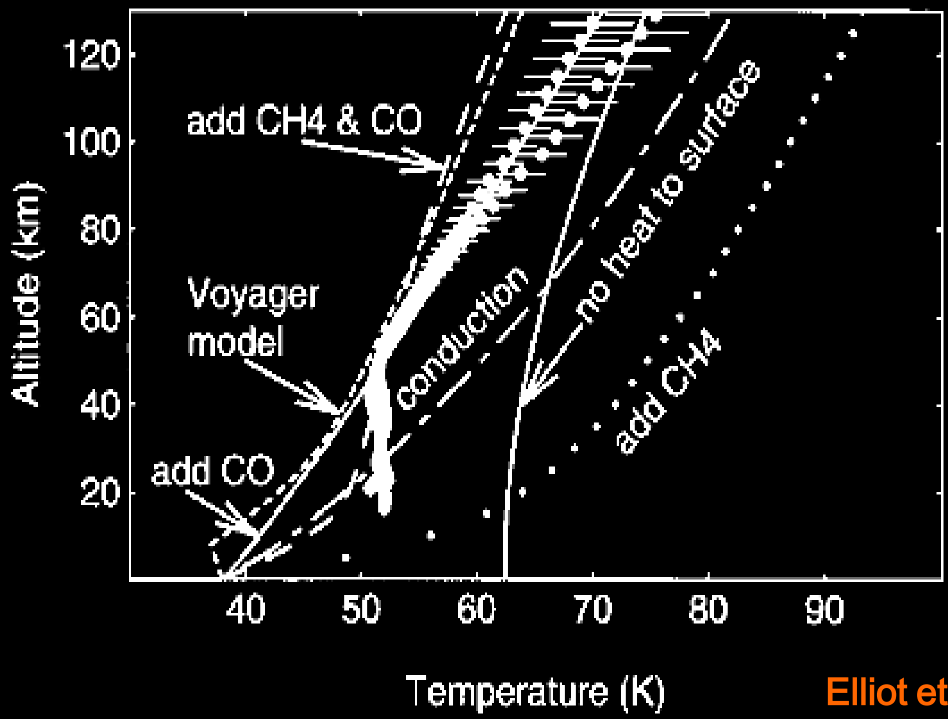
V (North-South) Winds

U (East-West) Winds



U-V Wind Vector Field

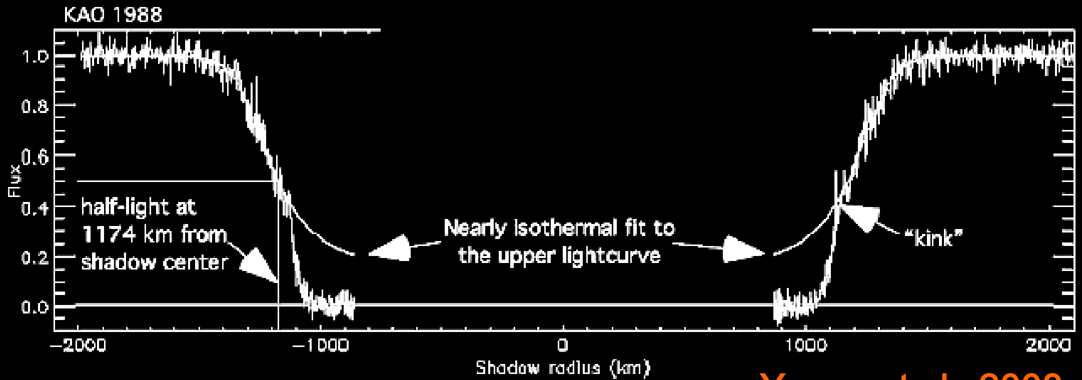
Triton's Atmospheric Structure



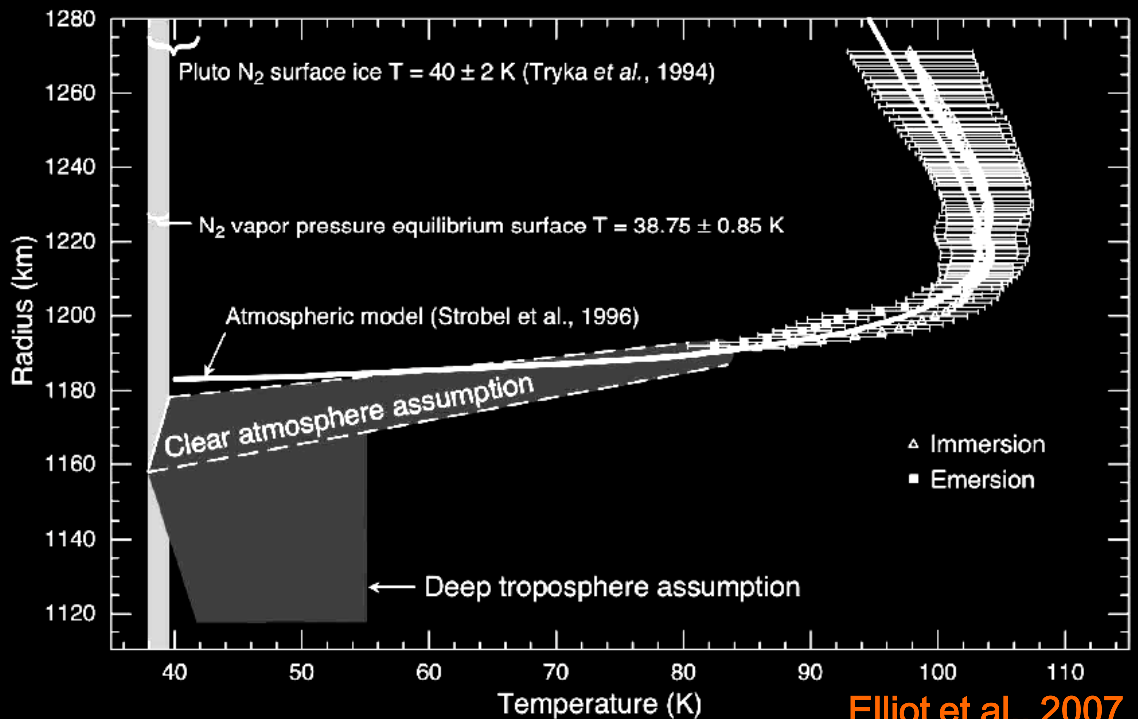
Elliot et al., 2000b

- July 1997 stellar occultation
- T= 95º K @ 300 km (Voyager 2), 50º K @ 50 km altitude
- Surface pressure increase to 19 µbar from 14 µbar at Voyager 1989 encounter

Pluto's Atmospheric Structure



Young et al., 2008



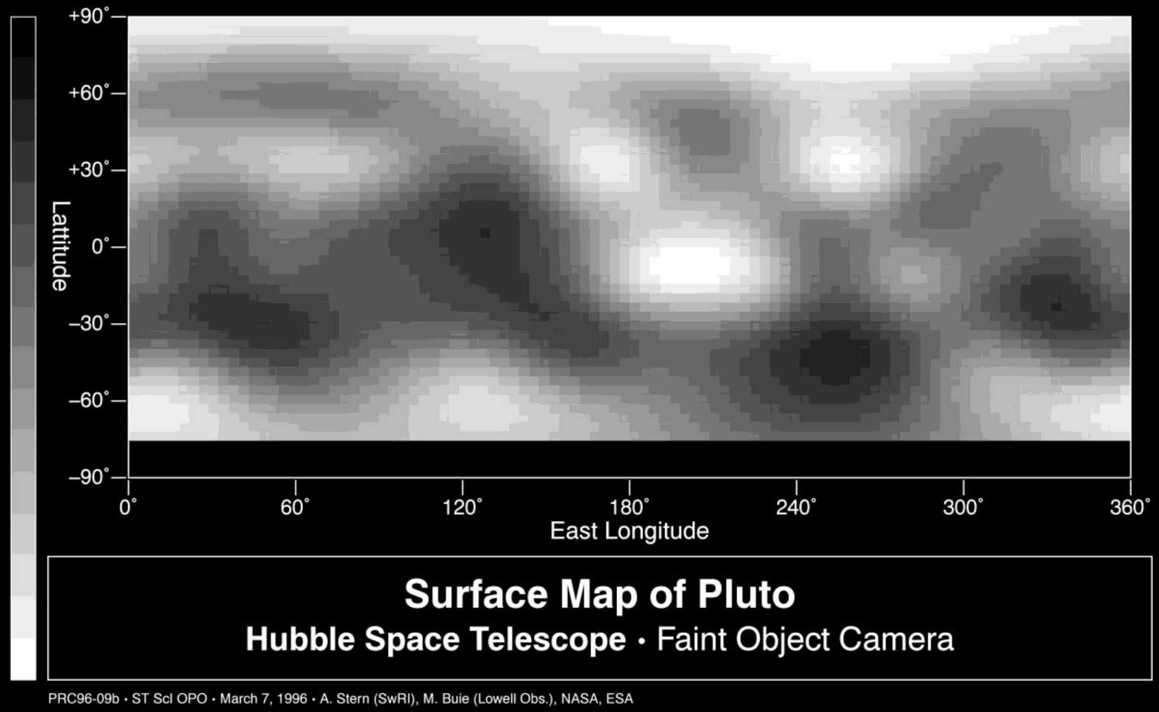
Elliot et al., 2007

- "Kink" in occultation light curve
  - Haze
  - Temperature gradient
- Pressure doubled between 1988-2002
- Troposphere ?

Changes to Ames GCM for Phase 1, Part 2 (N_2/CH_4 Atmosphere)

- Include radiative code for CH_4 assuming an N_2/CH_4 mixing ratio of 0.5% (L. Young, Lellouch)

- Define surface albedo map (E. Young, Stern, Buie)



Atmosphere Comparison

Earth

Atmosphere constituents

78% N_2, 21% O_2

Prime condensate

H_2O

273

Mars

Atmosphere constituents

95% CO_2, 3% N_2

Prime condensate

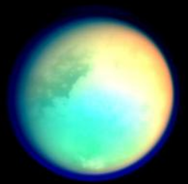
CO_2

210

Titan

Atmosphere constituents

98% N_2, 2% CH_4



Prime condensate

CH_4

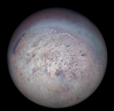
95

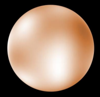
Triton

Pluto

Atmosphere constituents

99+% N_2





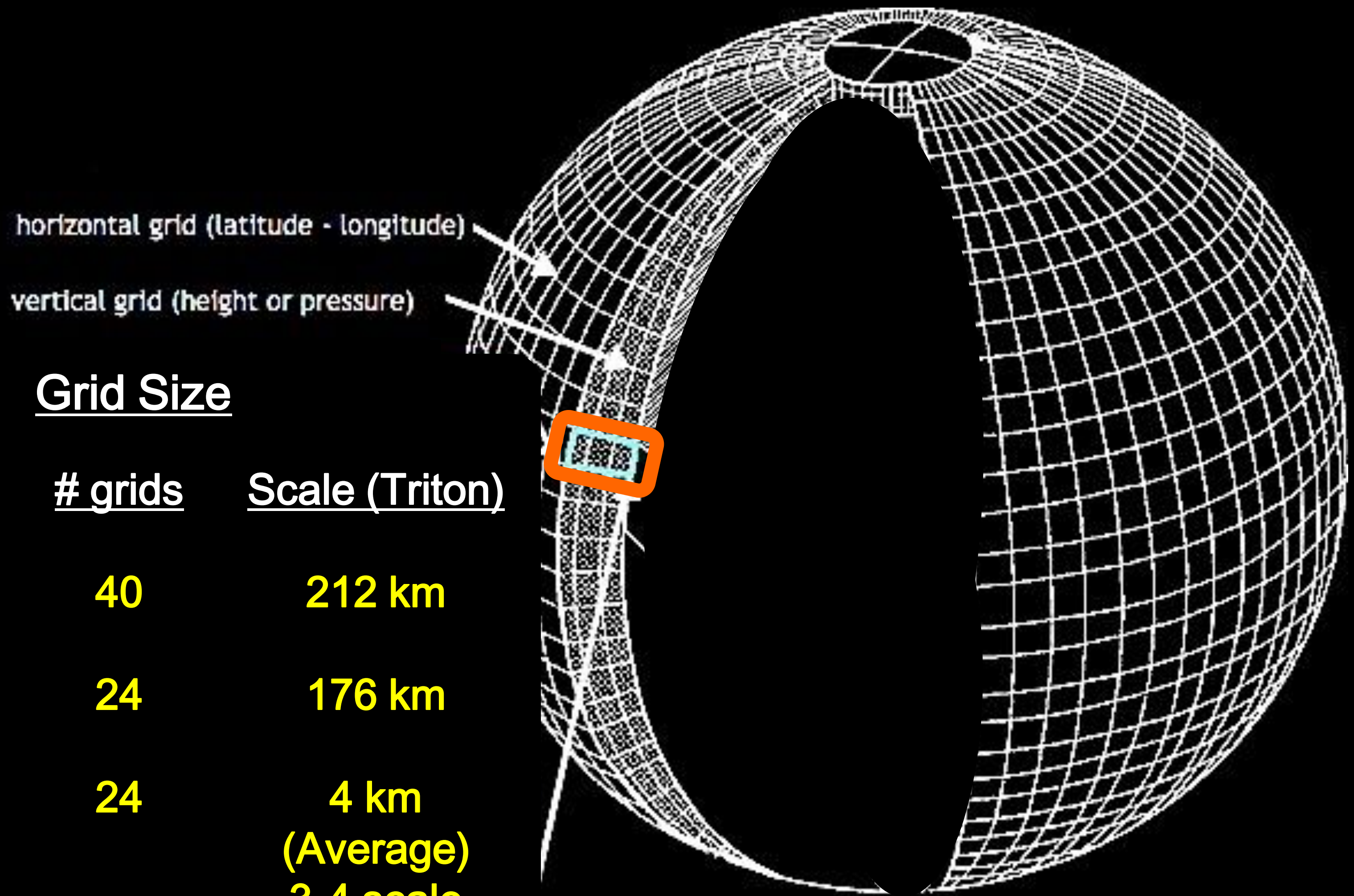
Prime condensate

N_2

35-50

Surface Temperature °K

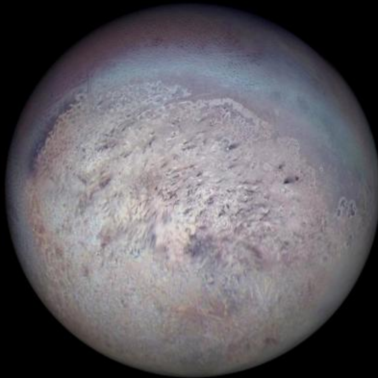
Simulation Grid Size



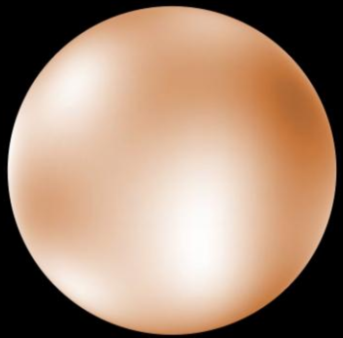
Grid Size

Dimension	# grids	Scale (Triton)
Longitude	40	212 km
Latitude	24	176 km
Vertical	24	4 km (Average) 3-4 scale heights

Triton and Pluto -
Twin Kuiper Belt Objects



Triton



Pluto

Radius (km)	1352.6 ± 2.4	1152 ± 32	
Density (g/cm^3)	2.054 ±0.032	2.03 ±0.06	
Surface gravity (m/s^2)	0.78	0.65[1]	[1]assuming Pluto radius = 1152 km
Rotation rate (day)	5.877	6.387	
Inclination	129.6°[2]	119.6°	[2]w.r.t. Neptune's orbital plane
a (AU)	30.069 (Neptune)	39.482	
e	0.009 (Neptune)	0.2488	
Orbital period (year)	163.72	248.09	

Surface Ice & Atmospheric Composition

	Triton	Pluto	
Surface Composition & Abundance	N_2 (> 99%) CH_4 (0.05%) CO (< 0.1%) CO_2 (< 0.2%)	N_2 (98%) CH_4 (1.5%) CO (0.5%)	
Surface Temperature	38° K	38-55° K	
Surface Pressure	14-19 μbar	7.5-24 μbar	
Atmosphere Scale Height	15 km @ 40K 38 km @ 100K	18 km @ 40K 46 km @ 100K	
Atmosphere CH_4/N_2 Mixing Ratio	0.01% (Estimated)	0.48 +1.26/-0.35%[1] 0.55 +/-0.11%[2] (Measured)	[1]Young et al., 1997 [2]Lellouch et al., 2009
Atmosphere CO/N_2 Mixing Ratio	0.015% (Estimated)	0.075% (Estimated)	

Pluto Atmospheric Collapse

- Significant reduction in Pluto's surface pressure between perihelion (29.66 AU) and aphelion (49.31 AU)

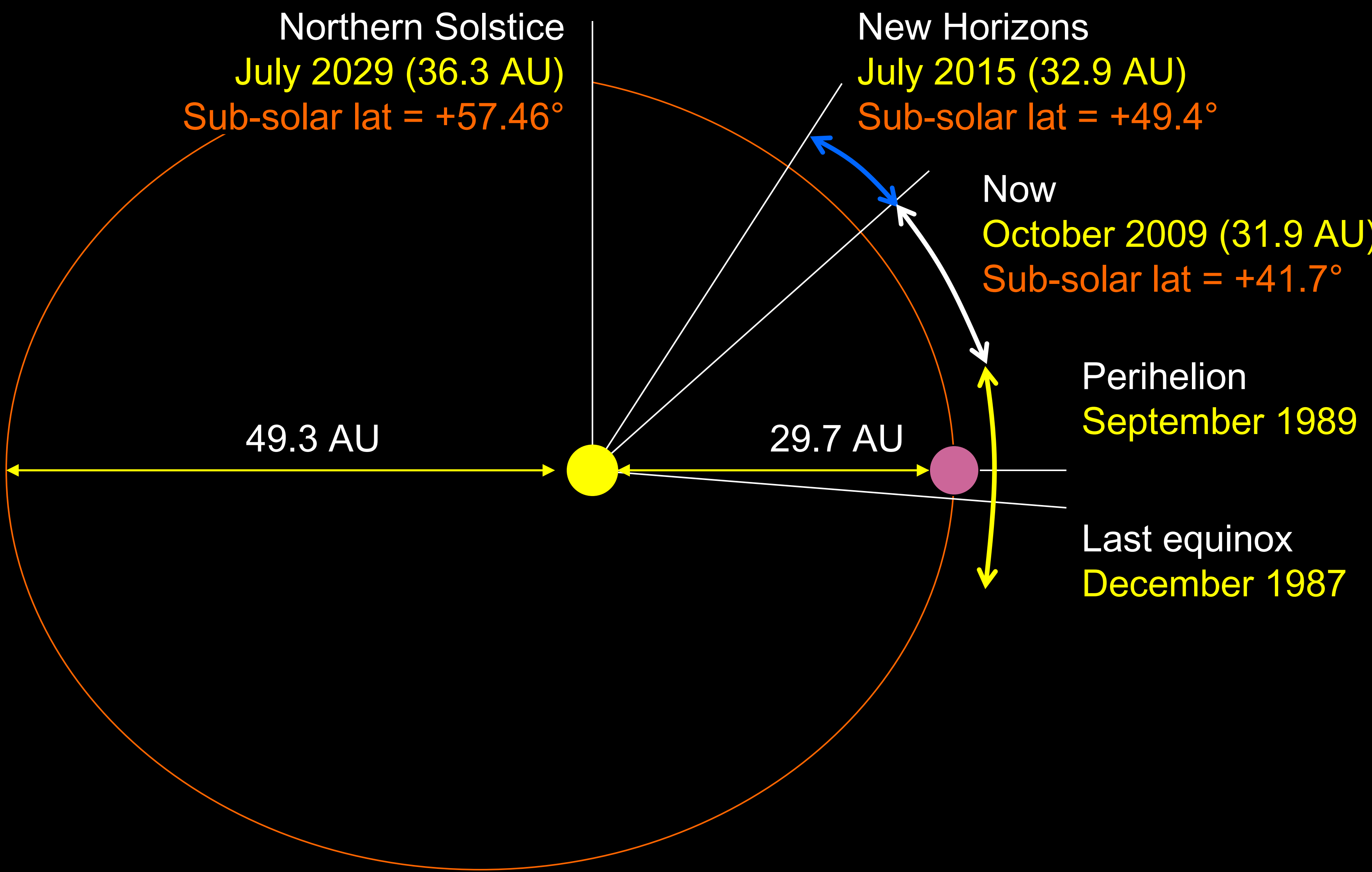
Set ε = 1.0, A= 0.66

Event	Date	Distance To Sun (AU)	Pluto Equil. Temperature	N_2 Surface Pressure
Perihelion	Sept-1989	29.66	38.7° K	28.5 μbar
Triton distance	Sept-1997	30	38.5° K	25 μbar
Now	Oct-2009	31.9	37.4° K	12.3 μbar
New Horizons	July-2015	32.9	36.8° K	8.3 μbar
	Apr-2024	35	35.7° K	3.8 μbar
	Jan-2043	40	33.3° K	0.6 μbar
	Feb-2067	45	31.5° K	0.1 μbar
Aphelion	Feb-2114	49.31	30° K	22 nbar

Pluto

- Second largest “dwarf” planet
- System of three moons
  - Charon (radius = 603 km, distance = 17,536 km)
  - Nix (radius = 23-68 km, distance = 48, 708 km)
  - Hydra (radius = 30-84 km, distance = 64,749 km)
- 3:2 resonance with Neptune
- Discovered by Clyde Tombaugh
- New Horizons to pass within 10,000 km with a relative velocity of 13.8 km/s on July 14, 2015

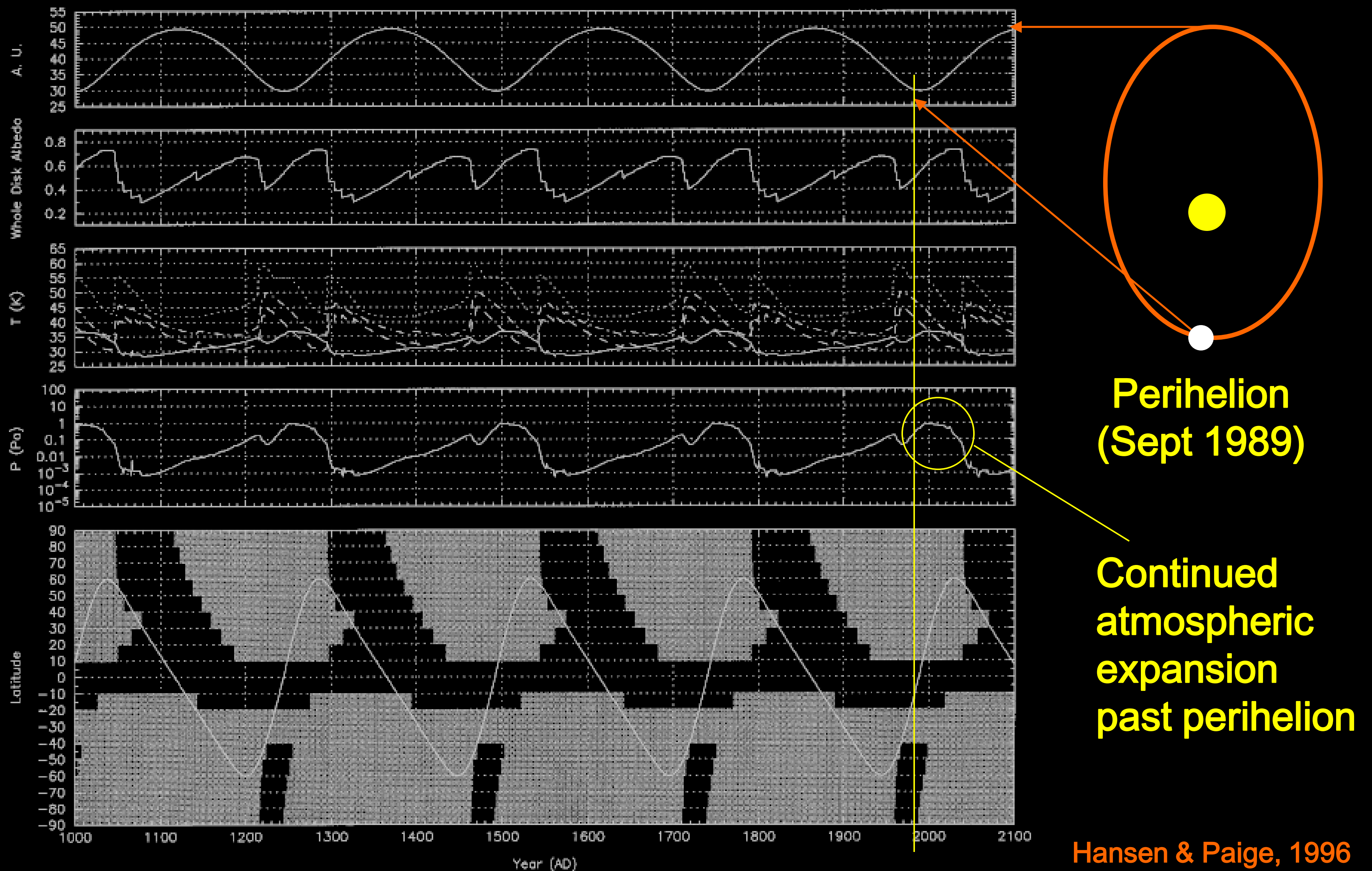
Pluto Simulation Windows



Thermal Modeling

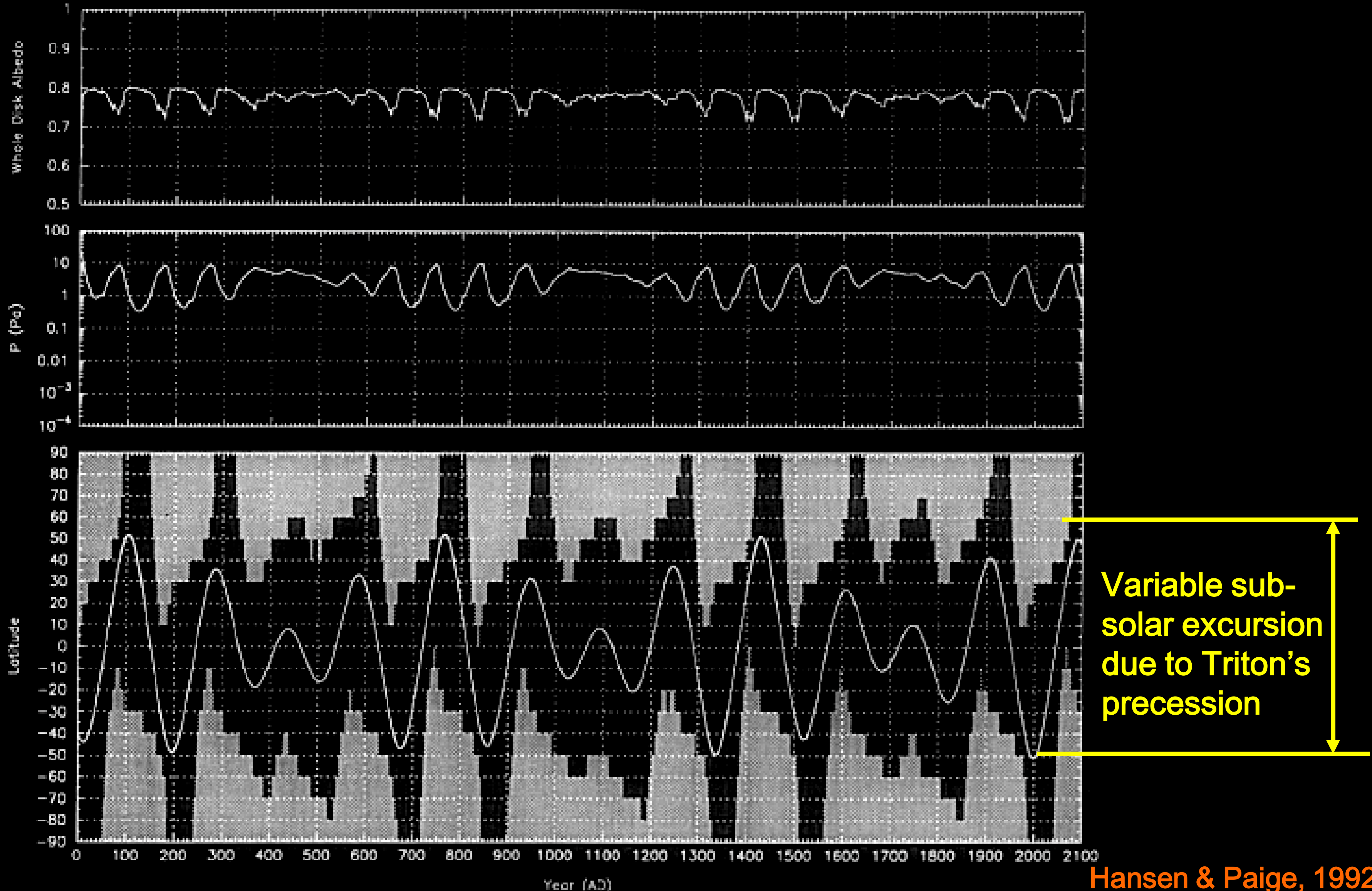
- Hansen & Paige, 1992 (Triton), 1996 (Pluto)
- Multi-orbit thermal model to constrain physical parameters affecting seasonal N_2 frost condensation and sublimation patterns
- Model condensation and sublimation of N_2
- Model orbital dynamics
- Model multi-layer substrate
- No modeling of atmosphere dynamics

Pluto Thermal Modeling Results



Hansen & Paige, 1996

Triton Thermal Modeling Results



Hansen & Paige, 1992