

# Understanding cam/model\_mod's highest\_obs\_pressure\_Pa and highest\_state\_pressure\_Pa

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# Background



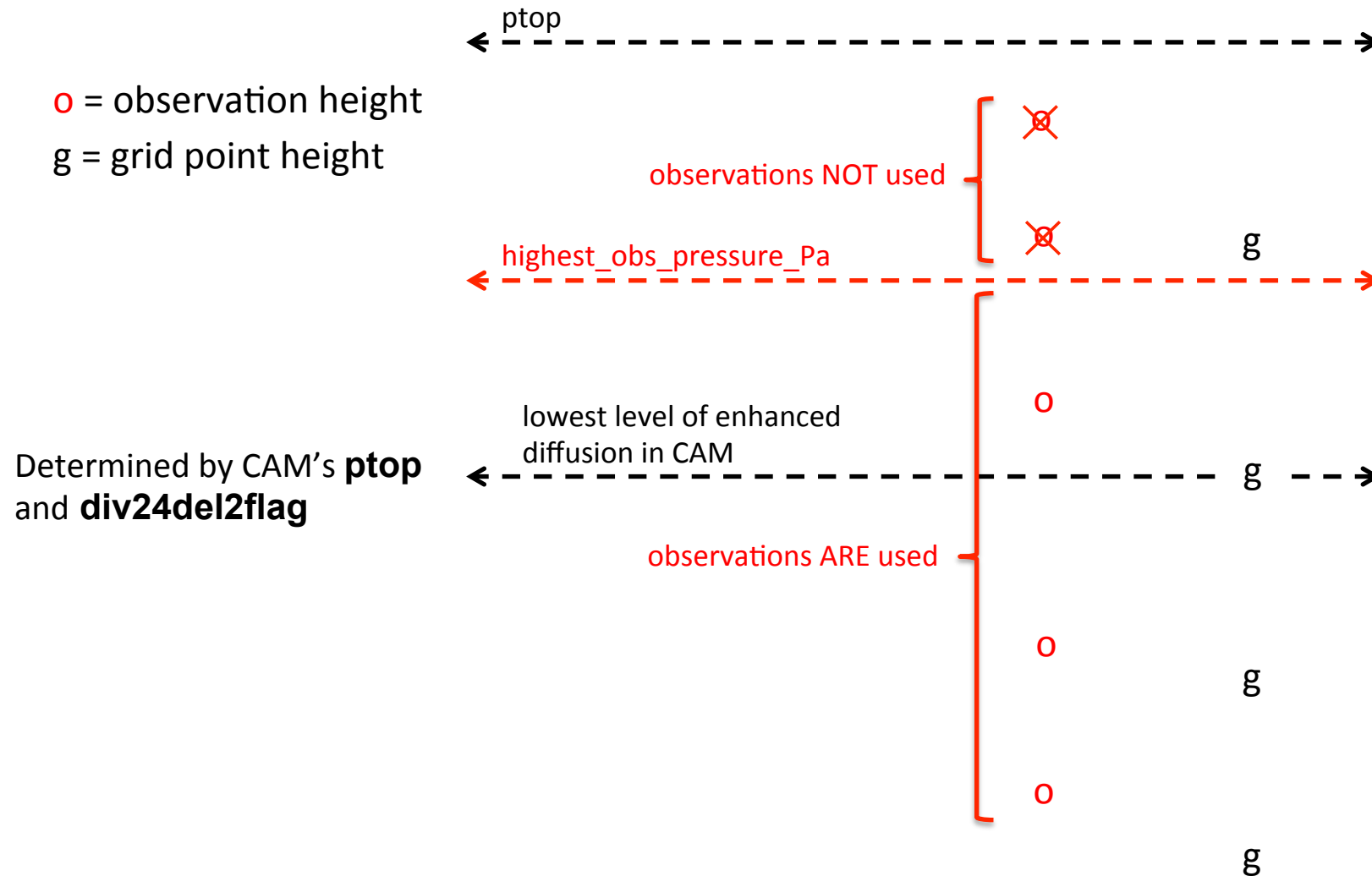
CESM's atmospheric components have a “sponge” region at the top of the model to reduce noise, reflection of vertically propagating waves off of the model top, and/or excessive jets.

In addition to CAM-FV's basic advection operator diffusion, it has a selection of algorithms available, which add diffusion in the top few levels. This extra diffusion is controlled by **div24del2flag** in `dynamics/fv/cd_core.F90`.

CAM-SE has “regular diffusion” added in the top 3 layers (controlled by **nu\_top** in `dynamics/se/share/prim_advance_mod.F90`), which also increases with height.

The model state does not respond well to being modified by data assimilation in the extra diffusion levels.

# Map of Vertical Space: grid points

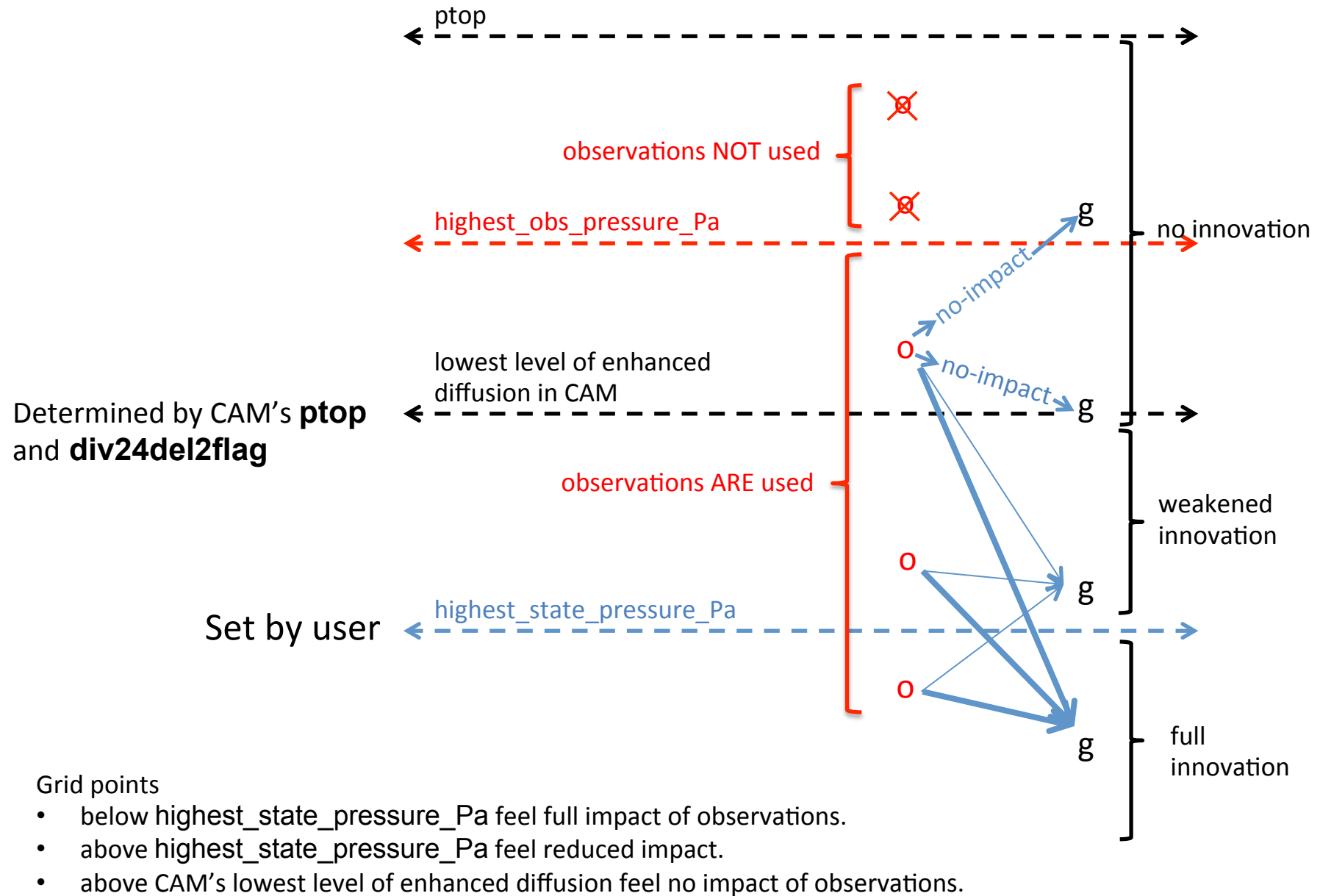


Model\_mod's namelist variable **highest\_state\_pressure\_Pa** controls the size of the innovations which happen in the upper model levels. We recommend using a value which makes the innovations be 0 in the levels where CAM has enhanced diffusion. In what follows, we show and derive the *minimum* value of **highest\_state\_pressure\_Pa** which will achieve our recommendation above.

There are several strategies for choosing a value, depending on how much you want to know about the algorithm:

- ① Use the values in the table below (which should be the defaults in `input.nml`)
- ② If you want more levels to be damped more, use a larger value, and vice versa.
- ③ If you want to know what the damping profiles look like, how they're calculated, and what to do if you use non-default cutoff and `vert_normalization_YYY`, read the rest of this document.
- ④ If you're not happy with the profile shapes, modify model\_mod to use a different profile (e.g. change 'n', below).

# Map of Vertical: Innovations



## Table of Common Vertical Coordinate Data



Default DART namelist values used to calculate DART's **highest\_state\_pressure\_Pa** ( $H_{Pa}$ ) in this table:

cutoff = 0.2,  
vert\_normalization\_pressure = 20000.0,  
vert\_normalization\_scale\_height = 2.5,

Calculations are shown after the table.

div2: CAM-FV's  
div24del2flag = 2

del2: CAM-FV's  
div24del2flag = 24

Model	# levels	$p_{top}$	div2 diffusion levels	$H_{Pa}$ (div2)	del2 diffusion levels	$H_{Pa}$ (del2)
CAM4-FV CAM5-FV	26 30,32	220 Pa	851 Pa (levels 1-2)	9370 Pa (levels 1-8)	1591 Pa (levels 1-3)	10500 Pa (levels 1-9)
WACCM4 -FV WACCM5	66 70	$4.5 \times 10^{-4}$ Pa (19.22 s.h.)	$1.74 \times 10^{-3}$ Pa (17.9 s.h., levels 1-3)	$9.2 \times 10^{-3}$ Pa (16.2 s.h., levels 1-6)	$3.26 \times 10^{-3}$ Pa (17.2 s.h., levels 1-4)	0.0183 Pa (15.5 s.h., levels 1-7)
CAM6	46? 60? 70?	?				
CAM-SE	26,30	220 Pa	X	X	same as CAM-FV	same as CAM-FV

## Goal: Algorithm



The algorithm in `cam/model_mod`, which reduces the influence of observations on state variables in CAM's extra diffusion layers, does this by increasing the "distance" between the observation and the state variable in `model_mod:get_close_obs()`. In DART, distance is a bit of an abstraction. The horizontal distance is the distance along the surface of the earth (radians), but the vertical distance is in different units, which are scaled into radians by the user's choice of **`vert_normalization_YYY`**. Because of the localization function used in DART, larger distance results in smaller innovation. So "distance" can be manipulated to control the influence of an observation on a state variable.

The levels subject to this innovation damping are controlled by the namelist variable **`highest_state_pressure_Pa`** ( $H_{Pa}$ ). The higher the state variable is above this level, the more distance is added to the nominal distance. At some height the new distance is larger than  $2 \times \text{cutoff}$  (normalized by **`vert_normalization_`**) and the state variable will not be affected by any observations. The recommended value of  $H_{Pa}$  will make this happen in all of CAM's extra diffusion layers, but all state variables below CAM's extra diffusive layers will be impacted to some extent by the observations. Users are free to choose another value, but should compare the results with an assimilation using the recommended value of  $H_{Pa}$ .



# Algorithms: CAM's 2<sup>nd</sup> Order Divergence Damping Coefficient



Div2 diffusion (div2del2flag = 2 in the CAM namelist):

$$\tau_k = \max \left\{ 1.0, 8 \left[ 1 + \tanh \left( \ln \left( \frac{p_{\text{top}}}{p_k} \right) \right) \right] \right\} \quad (\text{PHL}^* \text{ Eq (14) without spurious } \mu_2) \quad (2)$$

$p_{\text{top}}$  = pressure at model top (hyai(1))

$p_k$  = pressure at “mid-point” level k

Layers k are subject to this damping if  $\tau_k > 1$ :

$$p_k < p_{\text{top}} e^{\left[ \tanh^{-1}(1-1.0/8) \right]} < 3.87 p_{\text{top}} \quad (3)$$

CAM and WACCM have different  $p_{\text{top}}$  values, so there will be different number of damped levels (see Table 1).

\*Peter H. Lauritzen, et al., 2011: **Implementation of new diffusion/filtering operators in the CAM-FV dynamical core** *Int. J. High. Perform. C.*, Vol. 26 (Issue 1), pp. 63–73. DOI:10.1177/1094342011410088 (June 2, 2011)

# Algorithms: CAM's "Laplacian" Damping Coefficient



Del2 Damping\* (div24del2flag = 24):

$$\tau_k = 8 \left[ 1 + \tanh \left( \ln \left( \frac{p_{\text{top}}}{p_k} \right) \right) \right]$$

Layers  $k$  are subject to this damping if  $\tau_k \geq 0.3$ , (PHL Eq (21)), or when

$$p_k < p_{\text{top}} e^{\left[ \tanh^{-1}(1 - 0.3/8) \right]} < 7.234 p_{\text{top}} \quad (4)$$

CAM and WACCM have different  $p_{\text{top}}$  values, so there will be different number of damped levels (see Table).

\*Peter H. Lauritzen, et al., 2011: Implementation of new diffusion/filtering operators in the CAM-FV dynamical core *Int. J. High. Perform. C.*, Vol. 26 (Issue 1), pp. 63–73. DOI:10.1177/1094342011410088 (June 2, 2011)

## Algorithms: CAM's Advection Operator Diffusion



The advection operator diffusion goes to first order (more diffusion) in the top levels where  $k \leq k_{\max}/8$ .

So far we have not found the need to set  $H_{pa}$  based on this algorithm.

Since  $H_{pa}$  should be set below the div2 and/or del2 diffusion levels, which are just a few levels at the top, there will be some damping of obs impacts at most, maybe all, of the levels where the advection operator is first order.

## DART's highest\_state\_pressure\_Pa for vert\_coord = 'pressure'



So we want an algorithm which increases the “distance” from an ob to a state variable smoothly from its nominal distance lower down to something larger than twice the cutoff at the lowest level where CAM has extra diffusion. After some experimentation, we currently add a weighted distance given by:

$$\Delta d = \left[ \frac{(H_{Pa} - g)}{(H_{Pa} - p_{top})} \right]^n (H_{Pa} - g) \quad (5)$$

$g$  = the pressure at the grid point of interest (in this case the lowest extra diffusion level in CAM)

$H_{Pa}$  = highest\_state\_pressure\_Pa

$p_{top}$  = pressure at the model top

$n$  = some power of the weighting function, currently 1.0

We require that  $\Delta d \geq 2 \text{ } c \text{ } v$ , where  $c$  = cutoff,

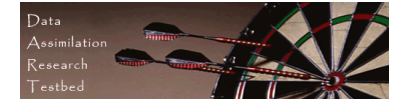
$v$  = vert\_normalization\_pressure

Solving the quadratic equation yields

$$H_{Pa} = g + cv \left\{ 1 + \sqrt{1 + \frac{2(g - p_{top})}{cv}} \right\} \quad (6)$$

The negative root has been chosen based on it yielding  $H_{Pa}$  below CAM's damped levels ( $g$ ).

## Vertical Profiles for Pressure vert\_coord

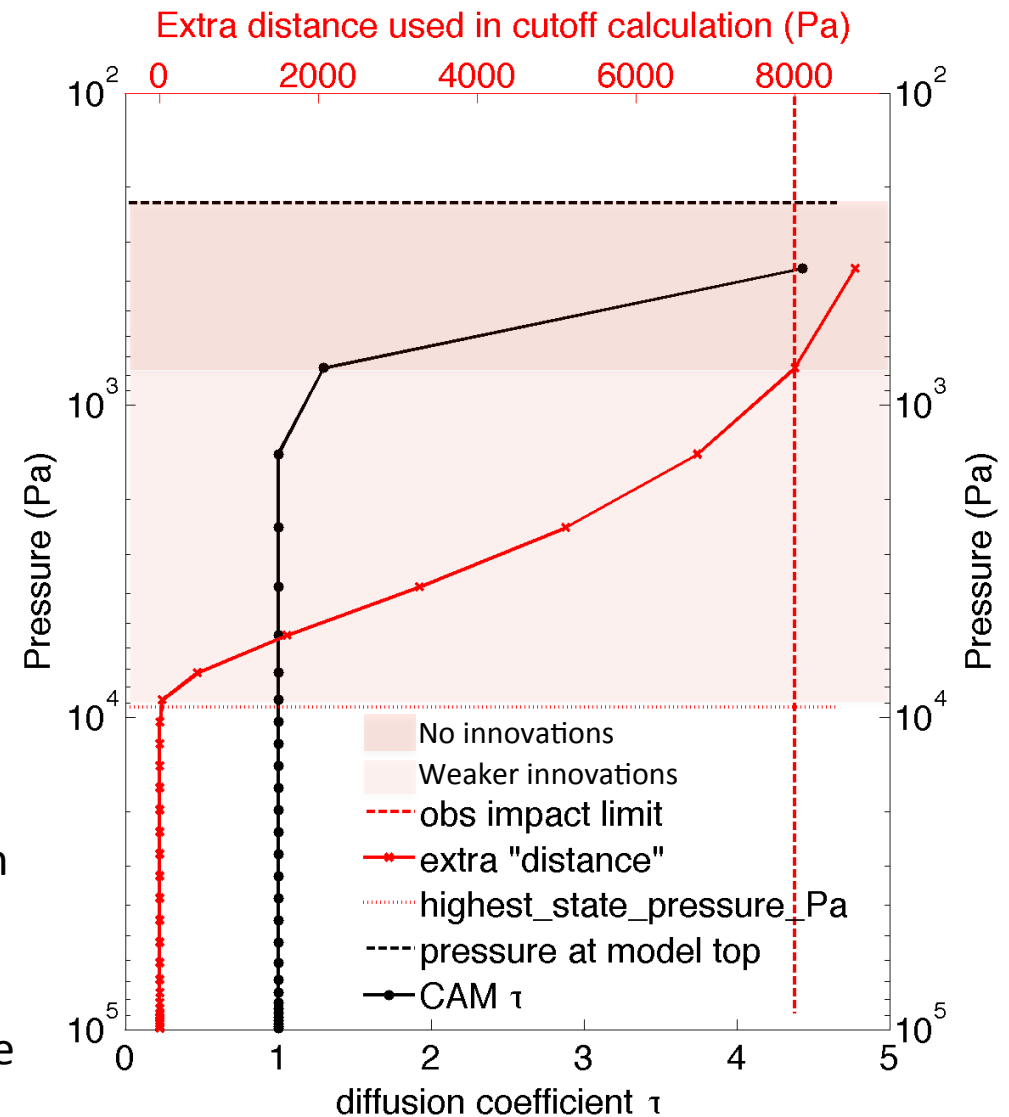


This shows how the distance (which is added to the nominal distance between an ob and gridpoint) is 0 below highest\_state\_pressure\_Pa, and increases smoothly upwards until it is larger than  $2 \times \text{cutoff} \times \text{vert\_normalization\_pressure}$  at the lowest level where CAM's extra diffusion is active. So there are no innovations at and above that level, even if the ob and grid point are co-located, in which case the nominal distance is 0.

Similar plots can be generated using  
models/cam/matlab/highest\_state\_p\_Pa.m

30-level CAM5-FV with div24del2flag = 2

The top 2 levels in this example should have innovations = 0.



```
vert_normalization_pressure = 20000.000000 Pa/radian
cutoff                      = 0.200000 radians
diffusion_flag              = 2
file providing model levels = ~/DAI/Homme/caminput_ne30.nc 13
```

## DART's highest\_state\_pressure\_Pa for vert\_coord = 'log\_invP'



If **vert\_coord** = 'log\_invP' (scale height), then the signs of all 3 factors in Eq (5) are reversed (because scale height increases upwards, contrary to pressure) and the resulting expression for H is

$$H = g - cv \left\{ 1 + \sqrt{1 + \frac{2(H_{top} - g)}{cv}} \right\} \quad (7)$$

$g$  = the scale height of the level of interest (in this case the lowest extra diffusion level in CAM)

$H$  = scale height of  $H_{pa}$

$H_{top}$  = scale height of the model top

$n$  = some power of the weighting function, currently 1.0

The negative root has been chosen based on it yielding H below CAM's damped levels ( $g$ ). Then  $H_{pa}$  can be found from the definition of scale height ( $\ln(p_{surf}/p)$ ):

$$H_{pa} = 10^5 \text{Pa} \times e^{-H} \quad (6)$$

# Vertical Profiles for Scale Height vert\_coord

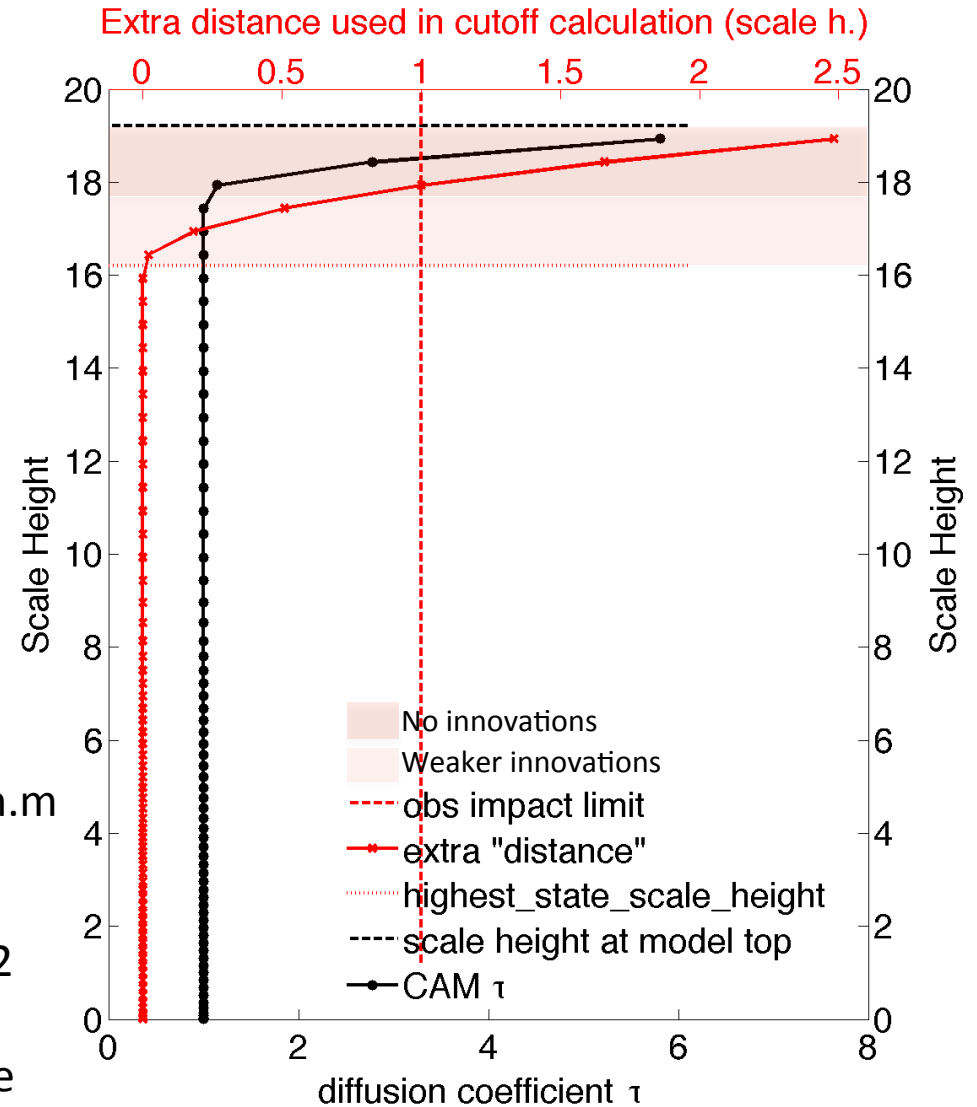


This shows how the distance (which is added to the nominal distance between an ob and gridpoint) is 0 below highest\_state\_scale\_height, and increases smoothly upwards until it is larger than  $2 \times \text{cutoff} \times \text{vert\_norm}$  at the lowest level where CAM's extra diffusion is active. So there are no innovations at and above that level, even if the ob and grid point are co-located, in which case the nominal distance is 0.

Similar plots can be generated using  
models/cam/matlab/highest\_state\_scale\_h.m

66-level WACCM4-FV with div24del2flag = 2

The top 3 levels in this example should have innovations = 0.



```
vert_normalization_scale_height = 2.500000 scale_height/radian
cutoff = 0.200000 radians
diffusion_flag = 2
file providing model levels = ~/DAI/WACCM/cam_initial_1.nc 15
```

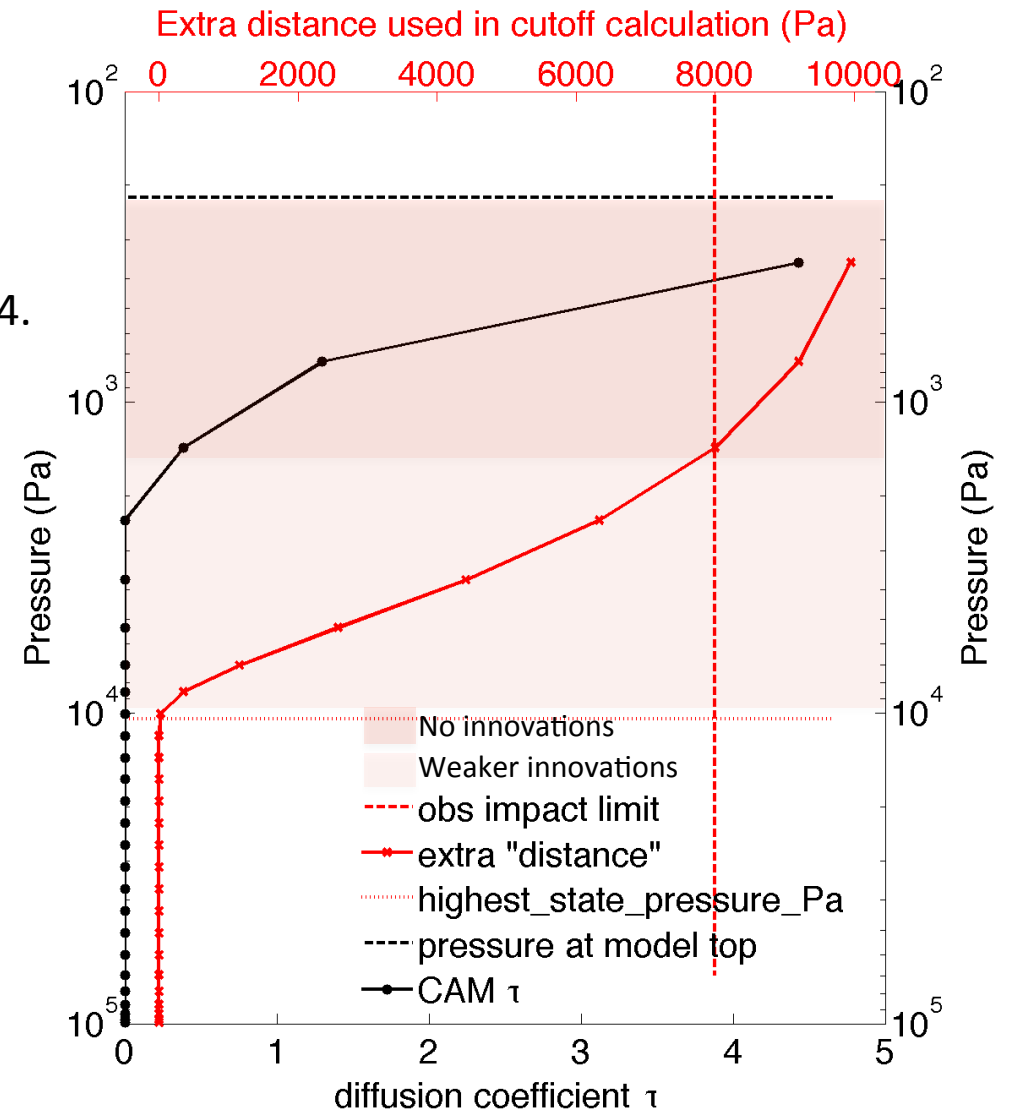
## Vertical Profiles for Pressure vert\_coord and div24del2flag = 24



Note that  $\tau = 0$  below the extra diffusion layers.

26-layer CAM4-FV with div24del2flag = 24.

The top 3 levels in this example should have innovations = 0.



```
vert_normalization_pressure = 20000.000000 Pa/radian
cutoff                       = 0.200000 radians
diffusion_flag               = 24
file providing model levels = ~/DAI/Kay/caminput.nc
```



# Varying Surface Pressure Concerns



CAM's hybrid coordinate system transitions from a blend of  $\sigma$  and pressure coordinates for the lower levels to pure pressure above some pressure level ( $\sim 18000$  Pa for CAM,  $\sim 8600$  Pa for WACCM). The  $\sigma$  coordinate depends on surface pressure, which varies from ensemble member to member. So we face the question of whether some members might exclude an observation because its location is slightly higher than `highest_obs_pressure_Pa`, while others include it because it's slightly lower.

For observations at a 'pressure', this won't happen for `highest_obs_pressure_Pa` in the pure pressure region of the model. But it can happen for `highest_obs_pressure_Pa` in the blended region. In that case, filter excludes the observation because it doesn't have an estimated observation for each member.

For observations at a 'height', it's more complicated. `Model_mod` converts the observation's vertical coordinate to `vert_coord`. The conversion of each level uses surface pressure, even in the pure pressure region. So each member will have a slightly different set of level heights, and may or may not exclude such an observation. As for observations at pressures, if any estimated observations are missing, filter will ignore that observation.

This is one possible explanation for filter using differing numbers of observations near `highest_obs_pressure_Pa` in different assimilations.

## DART Distance Units



As implemented in the code,  $\Delta d$  has units of radians, not Pa or scale height as derived previously. The 3 factors in Eq. (5) are distances, which are derived in radians using `location_mod/threed_sphere/get_dist()`, which applies the correct `vert_normalization` to the vertical component of distance.