Understanding cam/model_mod's highest_obs_pressure_Pa and highest_state_pressure_Pa

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Background

CESM's atmospheric components can have a "sponge" region at the top of the model to reduce grid scale 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 'divergence damping' at various 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.

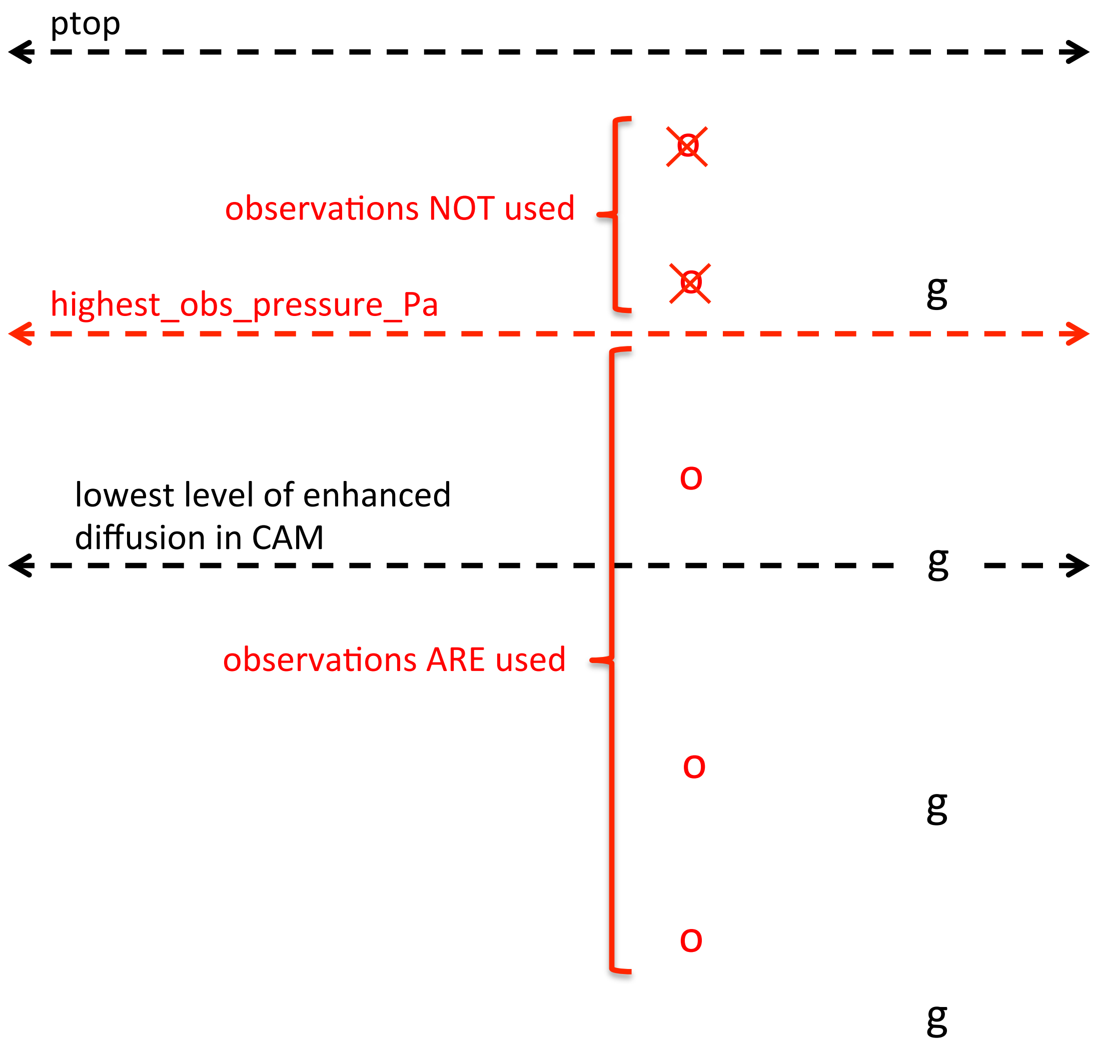
The model state may not respond well to being modified by data assimilation in the extra diffusion levels.

Map of Vertical Space: grid points

o = observation height

g = grid point height

Determined by CAM's `ptop` and `div24del2flag`



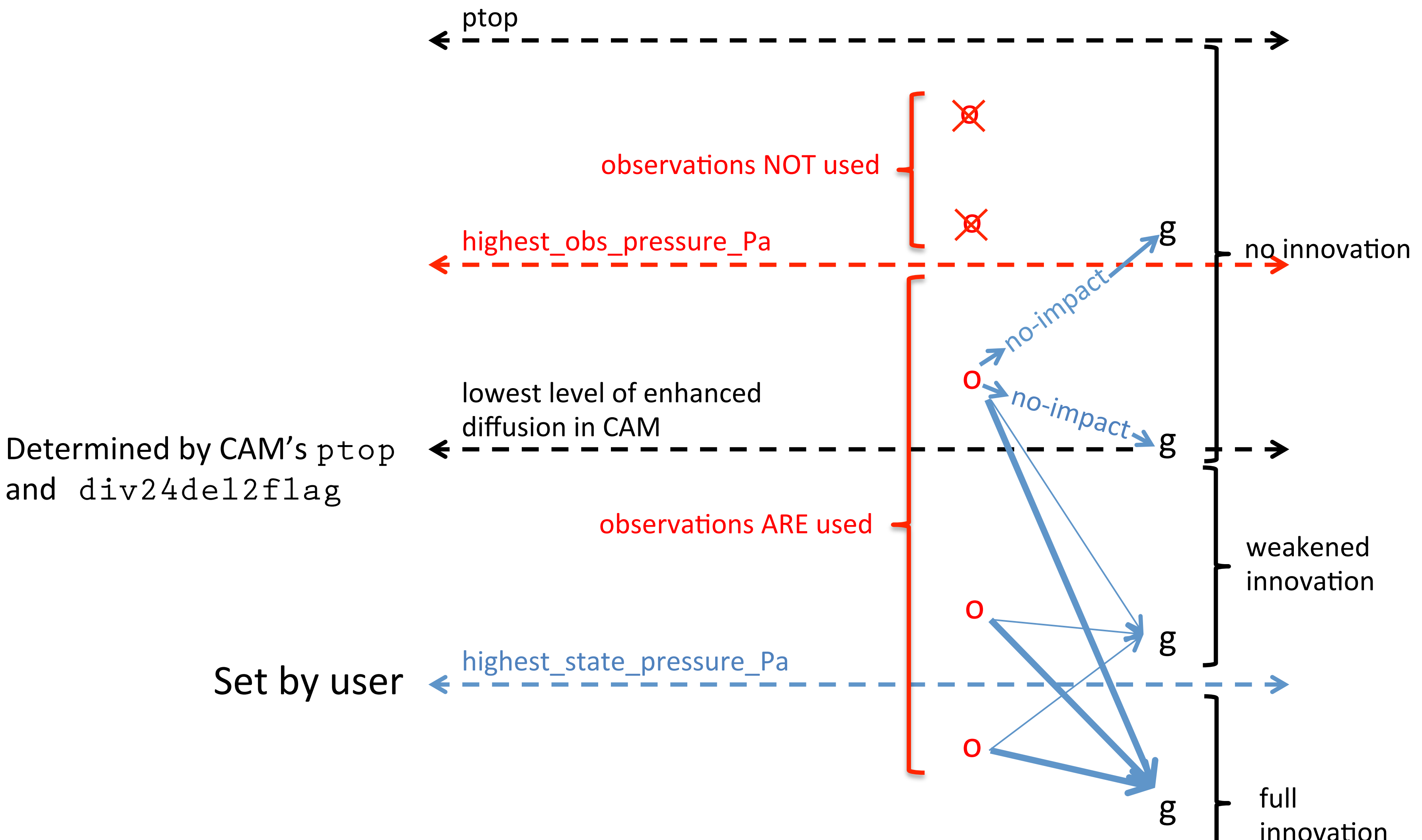
Recommendation and Strategies

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



Grid points

- below `highest_state_pressure_Pa` feel full impact of observations.
- above `highest_state_pressure_Pa` feel reduced impact.
- above CAM's lowest level of enhanced diffusion feel no impact of observations.

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 = 42`

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	4.5×10^{-4} Pa (19.22 s.h.)	1.74×10^{-3} Pa (17.9 s.h., levels 1-3)	9.2×10^{-3} Pa (16.2 s.h., levels 1-6)	3.26×10^{-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×`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 2nd Order Divergence Damping Coefficient

Div2 diffusion* (div24del2flag = 2 in the CAM namelist) is the default for FV:

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

p_{top} = pressure at model top (hyai(1))
p_k = pressure at "mid-point" level k

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

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

CAM and WACCM have different p_{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-FV's 4th Order Divergence Damping

To help control grid scale noise, especially in short forecast situations which DART uses, there can be a 4th order divergence damping which is applied throughout the atmosphere. When this is chosen (CAM's `div24del2flag = 4`), it may not be necessary to use DART's `highest_state_pressure_Pa` to reduce impacts at upper levels.

It may be necessary to increase CAM's dynamics time splitting (`nsplit`).

Algorithms: CAM's "Laplacian" Damping Coefficient

Del2 damping* was implemented to reduce polar night jets in long, high resolution simulations. This may not be an issue in the DART context. It is applied to the top levels, like div2, but is paired with div4 diffusion (see previous page) when choosing `div24del2flag` =42. Del2 can't be used by itself. Div4 may be a better choice.

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

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

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

CAM and WACCM have different p_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 $k \le k_{max}/8$.
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:

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

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

H_{Pa} = `highest_state_presure_Pa`

p_{top} = pressure at the model top

n = some power of the weighting function, currently 1.0

We require that $\Delta d \geq 2\,c\,v$, where c = `cutoff`,
v = `vert_normalization_pressure`
Solving the quadratic equation yields

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

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

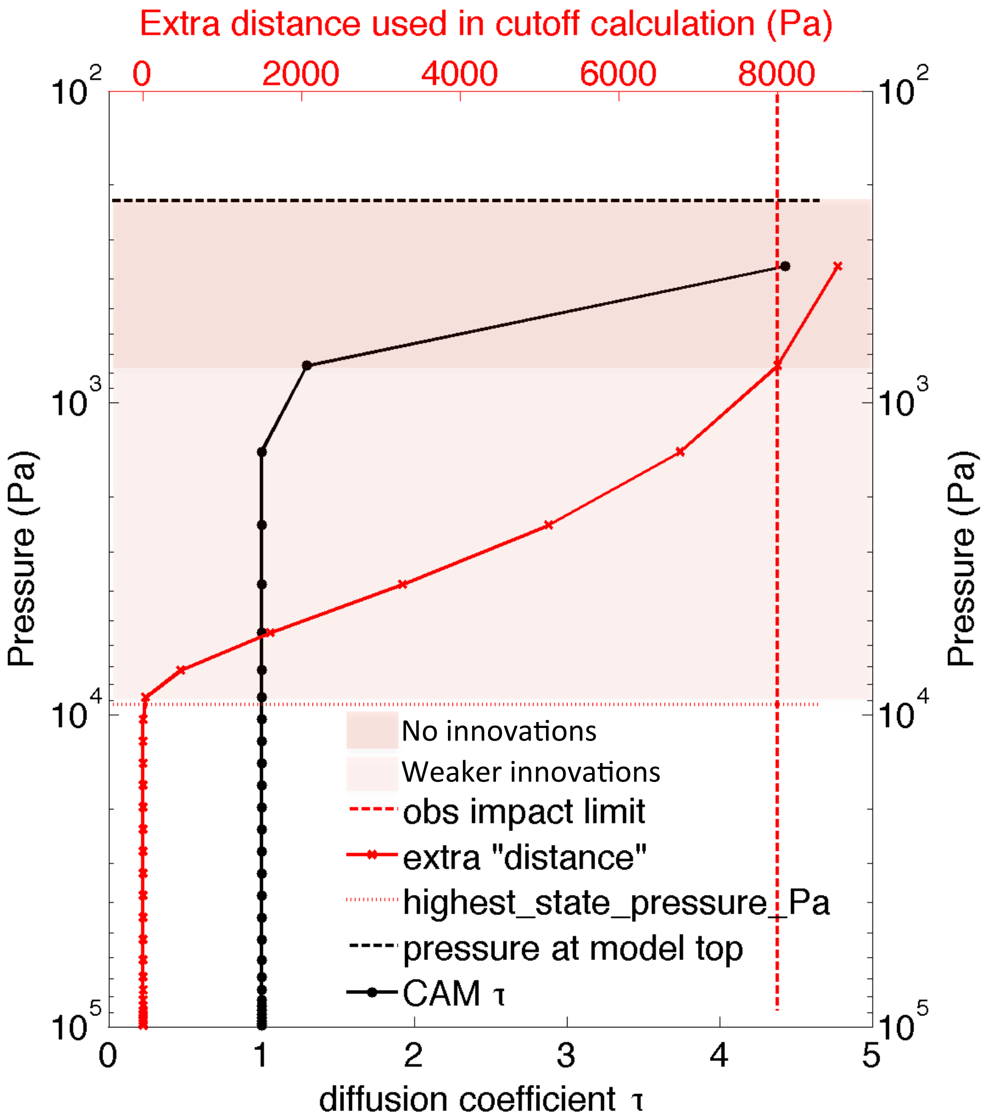
Vertical Profiles for Pressure `vert_coord`

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*`cutoff*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
```

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

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

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 ($\ln(p_{surf}/p)$):

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

Vertical Profiles for Scale Height

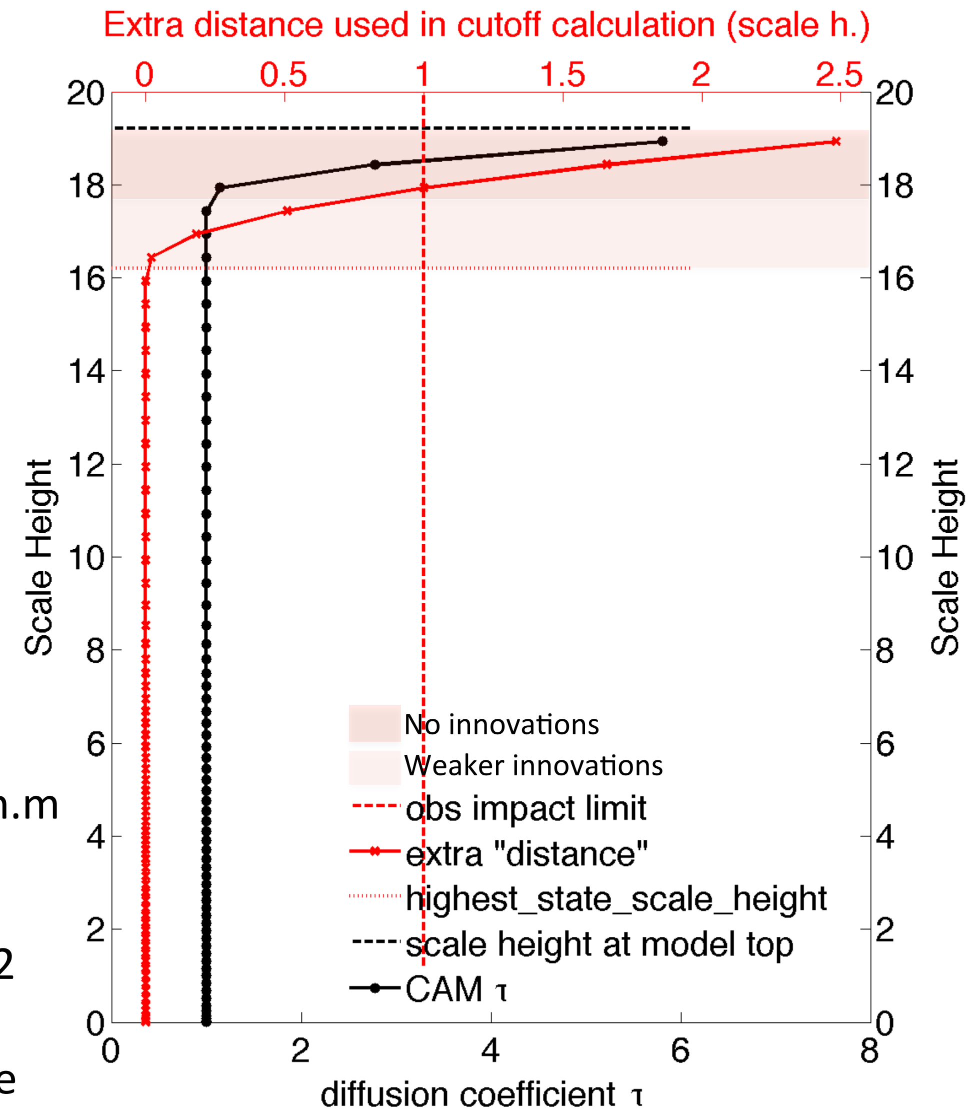
`vert_coord`

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*cutoff*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.



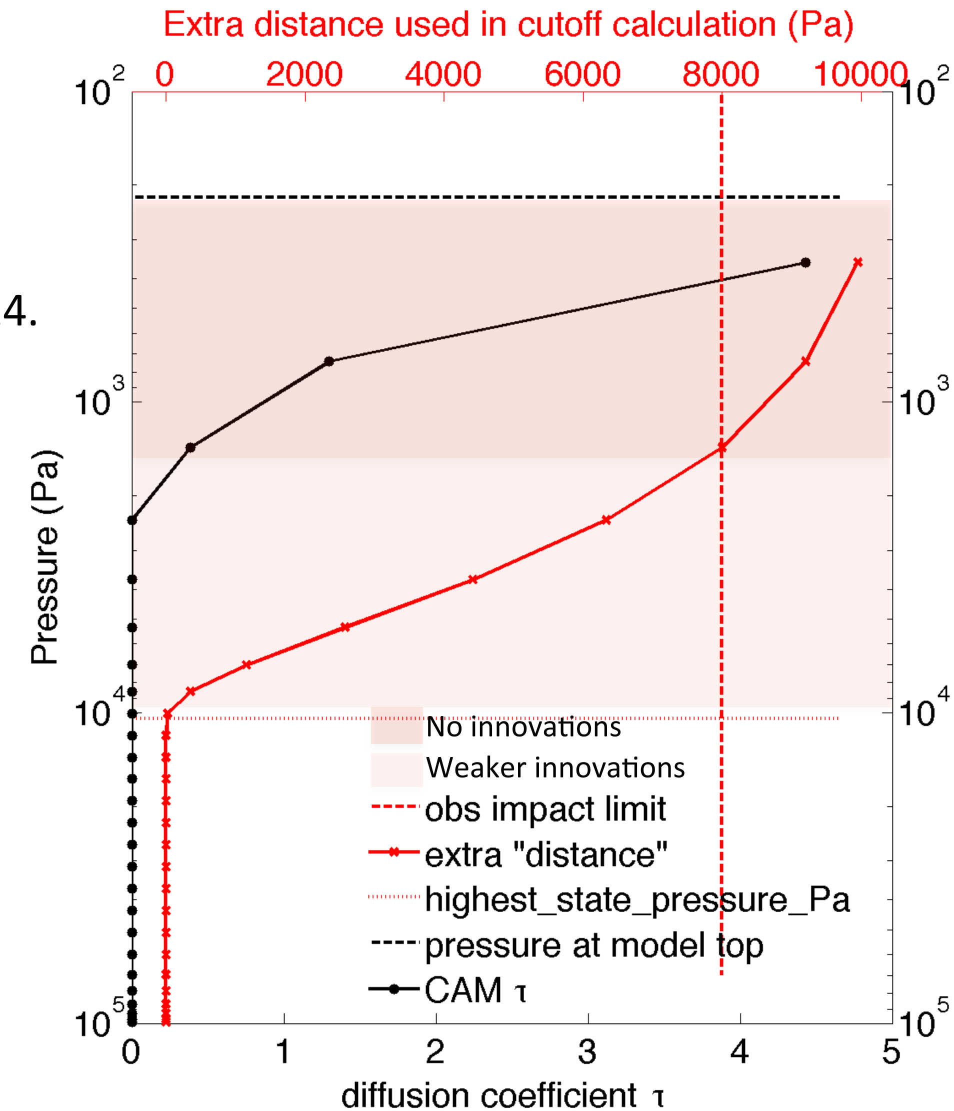

```
vert_normalization_scale_height = 2.500000 scale_height/radian
cutoff                          = 0.200000 radians
diffusion_flag                  = 2
file providing model levels     = ~/DAI/WACCM/cam_initial_1.nc
```

Vertical Profiles for Pressure `vert_coord` and `div24del2flag` = 24

Note that τ = 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 σ and pressure coordinates for the lower levels to pure pressure above some pressure level (~18000 Pa for CAM, ~8600 Pa for WACCM). The σ 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.

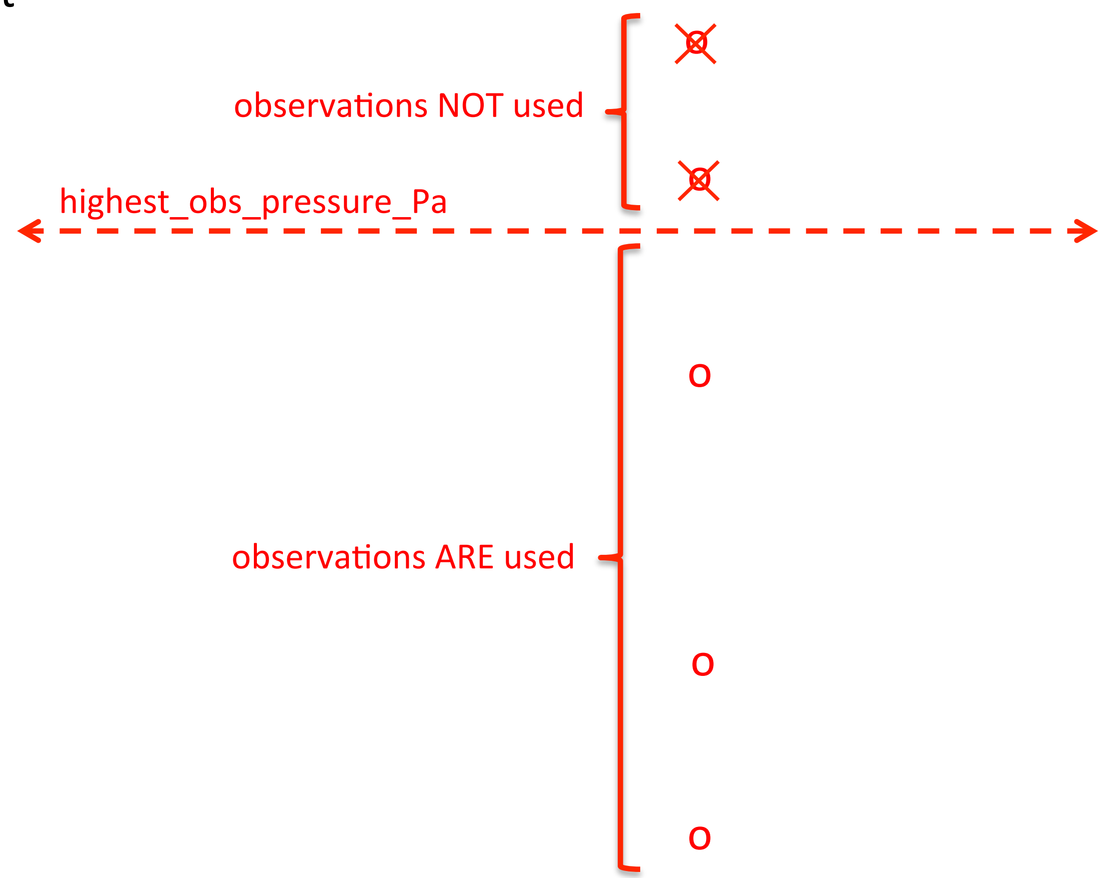
This is one possible explanation for filter using differing numbers of observations near `highest_obs_pressure_Pa` in different assimilations.

DART Distance Units

As implemented in the code, Δd 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.

Comparison of highest_obs and highest_state

o = observation height



Alternative to p_{top}

If I use $p_{lowest\_damped\_level}$ instead of p_{top} then the distance increment is no longer weighted, and H_{Pa} reduces to

$$H_{Pa} = g + 2cv$$

which is higher then (6), so more levels feel more impact of observations. It makes little difference near H because of the quadratic formula, and may not make much qualitative difference near the lowest damped level, because the tail of the Gaspari-Cohn function is also reducing the innovations there. But the weighting would be smoother there, approaching $\sim 1^2$ rather than $\sim 0.8^2$.