Comments from Referee 1 and Associated Responses:

Counteracting Influences of Gravitational Settling Modulate Aerosol Impacts on Cloud Base Lowering Fog Characteristics by N. H. Pope and A. L. Igel.

General:

This paper presents the interesting results of a single a single-column model, PAFOG model used to examine the results of aerosols and microphysics on marine, cloud-based lowering which has been associated with a portion of the process that can lead to marine fog. MISTRA, a microphysics scheme was included. An idealized case was presented in which a persistent stratus deck lowers at its base, becomes fog, and then rises back up over the course of 24 hours. Model variables included aerosol concentrations, gravitational settling, cloud top entrainment, vertical moisture flux, liquid water path, surface water deposition and fog water concentration. Meteorological variables include subsidence velocity above the boundary layer, geostrophic wind speed, air-sea temperature difference and rate of change of the sea surface temperature.

Presenting the results of this model and interpreting what this means is a very reasonable and useful thing to do. This is especially helpful as all marine fog studies are incomplete due to the impossibility of covering all of the possibilities/variables or even most of the possibilities/variables, so it is useful to see what the aerosols might do by themselves even if it is with a numerical model that has limitations and there are no direct data comparisons.

The writing is well done and the figures are excellent.

I have made only small suggestions. I would also ask that the remind the readers throughout the manuscript that they are referring to the model/simulations to distinguish when the actual marine conditions are being discussed.

Specific comments:

Line 23-25: Notably, the California coast and the Grand Banks represent two types of regions highly susceptible to marine fog, characterized by cold coastal upwelling (California) or cold protected waters with nearby western ocean boundary currents (Grand Banks).

Suggest something as: Notably, the California coast and the Grand Banks represent two types of regions susceptible to marine fog with cloud base lowering. The northern California case has a summer concentration of fog occurrence related to the wind driven cold water upwelling along the coast. Atlantic Canada over the shelf (including the

Grand Banks) has greater fog occurrence that includes factors of warm surface air blowing over colder water and synoptic scale forcing.

Changed to "The northern California case has a summer concentration of fog occurrence related to cold water upwelling along the coast, while Atlantic Canada over the continental shelf (including the Grand Banks) has significant fog occurrence related to high sea surface temperature (SST) gradients along a western ocean boundary current"

L29: Since stratus lowering is one of the most common fog…

Change to: Since stratus lowering is a fog formation mechanism along the California coast and Atlantic Canada.

Note: There is no direct statistical study to show that stratus is most common, or even that it is common in other world marine fog areas – just some studies to show that it does occur.

Changed to "Since stratus lowering is a common fog formation mechanism on the California coast (Pilié et al., 1979), many studies on stratus lowering fog have focused on that region"

L38-39 Although the sea surface is cool, studies have noted that the air is nonetheless cooler than the sea surface during CBL events.

Comment: State what studies show this. It would be more correct to say: Some studies (cite) show that the air is cooler than the sea surface during CBL events.

Note: That cooler air during CBL events in Atlantic Canada is contrary to that stated earlier in this paper that it is warm air traveling over cooler water to the north that forms fog over the Grand Banks or any part of Atlantic Canada.

Citations for Pilié et al. (1979), Koraˇcin et al. (2001), and Lewis et al. (2003) have been moved into the position that you recommend, though we have kept the original wording. It now reads "Although the sea surface is cool, studies (Pilié et al., 1979; Koraˇcin et al., 2001; Lewis et al., 2003) have noted that the air is nonetheless cooler than the sea surface during CBL events. Pilié et al. (1979) explains that the sea surface fluxes both sensible and latent heat into the boundary layer, counteracting moisture loss due to entrainment and supporting turbulent mixing.

Cooler air during CBL events in Atlantic Canada is contrary to the earlier explanation of warm air traveling over cooler water because these are distinct fog formation *mechanisms. The fog events that form from the advection of warm air over cold water are generally not formed through CBL.*

L39-40: The sea surface fluxes both sensible and latent heat into the boundary layer, counteracting moisture loss due to entrainment and supporting turbulent mixing

Change to: Off northern California, the sea surface fluxes of both sensible and latent heat into the boundary layer counteract moisture loss due to entrainment and supporting turbulent mixing.

changed

L41-42: Though differential advection can play a role in the setup of a CBL fog case (Wagh et al., 2021), it is typically conceived of as a Lagrangian process occurring within a column

Change to: Though differential advection can play a role in the setup of a CBL fog case (Wagh et al., 2021), it is has been conceived of as a Lagrangian process occurring within a column…

Changed to "it has been conceived of …"

Note: these are only a few case studies and are not a statistically supported analysis of what is typical.

L42-44: As long as the conditions of a subsidence-capped boundary layer and net cooling of the boundary layer persist, the cloud base will tend to lower.

Comment: Delete this sentence or provide citations that support this.

We do not believe that this requires citation because (assuming a stratus cloud already exists) then a boundary layer that is cooling will necessarily lead to more condensation and thus cloud growth. If subsidence prevents upward growth, then the cloud will grow downwards from its base. Therefore, cloud base will tend to lower if there is net cooling in a cloudy boundary layer that is capped by subsidence.

L64-65: While it is understood that aerosols can impact fog formed through cloud base lowering and that the response of CBL fog to aerosols is probably different to that of radiation fog, the relationship between aerosol and CBL fog is not well understood.

Comment: The focus of this manuscript is on aerosol and CBL. The comment about radiation fog is extraneous. Suggest removing it.

Changed to "While it is understood that aerosols can impact fog formed through cloud base lowering, the relationship between aerosol and CBL fog is not well understood."

L67-68: our aim is examine the microphysical processes of marine CBL fogs as well as the relationship between microphysics and meteorology.

Comment: "Meteorology" is too broad . Only a few general aspects of meteorology in the form of forcing are considered in this manuscript. Better: Our aim is to examine the microphysical processes of marine CBL fogs as well as the relationship between microphysics and some general meteorological forcing conditions.

Changed to "our aim is examine the microphysical processes of marine CBL fogs as well as the relationship between microphysics and several meteorological forcing conditions"

Line 84: campaign in the Grand Banks, PAFOG coupled with ERA5 advection terms performed well (Chen et al., 2021)

Comment: Change "Grand Banks" to on the "NW edge of the Grand Banks adjacent to Newfoundland".

changed

Line 96-98: The initialization run begins at 1400 UTC because initial tests showed this time to be associated with the daily maximum of cloud base height.

Comment: Change to: The initialization run begins at 1400 UTC because initial tests showed this time to be associated with the simulated daily maximum of cloud base height.

changed

Line 82-83: " the 2018 C-FOG campaign in the Grand Banks, "

Change to: "the 2018 C-FOG campaign around the SE Newfoundland coast and the NW edge of the Grand Banks,"

changed

Line 98-99: The initialization run begins at 1400 UTC because initial tests showed this time to be associated with the daily maximum of cloud base height.

Comment: Change to: The initialization run begins at 1400 UTC because initial tests showed this time to be associated with the simulated daily maximum of cloud base height.

changed

Line 122-124: Three of the parameters modify the meteorological background in which our fog case is forming. The first of these "back ground" variables is the subsidence velocity above the boundary layer (wsub) from 2.5 mm/s to 3.5 mm/s (Wood and Bretherton (2004)). The second is the geostrophic wind (Ug) which is varied from 5.0 m/s to 15.0 m/s.

Comment: What marine area do these parameters apply to? The world? Are these related to N. California or the Grand Banks? Please cite the supports for this.

Changed to " from 2.5 mm/s to 3.5 mm/s, which are reasonable values for the California coast" and added an additional citation (Koracin and Dorman, 2001).

*The Wood and Bretherton paper reports a mean subsidence strength of 3 mm/s at the top of the boundary layer for the California coast, though they report a typical boundary layer top of around 1000m. Koravcin and Dorman focus on the month of June specifically, when fog is common in the region, and they report that the boundary layer is typically less than 350m thick near the coast and that lower level divergence of around 1*10^{-5} m^2/s is common (and divergence is often as high as 2*10^{-5}). These values agree with the parameters of both inversion height and subsidence strength chosen for this experiment.*

Wood, R. and Bretherton, C. S.: Boundary layer depth, entrainment, and decoupling in the cloud-capped subtropical and tropical marine boundary layer, Journal of climate, 17, 3576–3588, 2004.

Koraˇcin, D. and Dorman, C. E.: Marine atmospheric boundary layer divergence and clouds along California in June 1996, Monthly Weather Review, 129, 2040–2056, 2001.

Line 126-127: In addition to these two parameters, we vary the rate of change of the sea surface temperature (dTsurf) from-2 to +2 K/day. This change mimics the effects of advection of the fog over a sea surface temperature gradient.

Comment: What marine area does this apply to? Please note how the advection of fog over a sea surface temperature gradient was constructed.

Added: "The modeled ocean surface warms or cools at a constant rate defined by dTsurf."

The range values for SST rate of change is conservative, since SST gradients of 0.02K/km are common off the coast of California and would realistically correspond to an instantaneous SST rate of change of 10 K/day or more if a column of air were being advected by the mean wind over that gradient. However, it is unrealistic that such a value would be sustained over the course of an entire day, so we chose a conservative range of constant SST rates of change in order to provide an idea of how advection over warmer or colder water impacts the rate of CBL. The sentence after "This change … over a sea surface temperature gradient" attempts to briefly explain the purpose of dTsurf.

Line 133, Table 1.

Comment: What areas does this data represent and how was it constructed?

Line 135-184: 3.1 Overall Response.

Comment: Please note these results are the simulated responses using the values in Table 1.

Changed the first sentence of the section to "We first look at the response of fog density and thickness in the model to the combinations of parameters shown in table 1."

Line 142. Fig. 2 Caption: CLWC, 2 times, should be CWC.

changed

Line 143. liquid water path of fog is typically enhanced by higher Na.

Change to: liquid water path of fog is correlated with higher Na.

changed

Line 143- 144: Figure 2 also elucidates the existence of "outlier" simulations. A subset of simulations with low Na and a cooling surface formed dense but atypically shallow fog layers.

Change to: In the lower right of Figure 2 are outlier simulations which are a subset of simulations with low Na and a cooling surface that formed dense but atypically shallow fog layers. (Yes?)

Changed to "In the lower right of figure 2 are outlier simulations, which are a subset of simulations with low Na and a cooling surface formed dense but atypically shallow fog layers"

Line 145-147: These simulations all ended with a much thinner boundary layer than they began with. The height of the inversion lowers by at least 100 m, with the lowering taking place after nightfall. Once fog forms in these simulations, it does not dissipate prior to simulation end.

Change to: All of these simulations ended with a much thinner boundary layer in which the height of the inversion lowered by at least 100 m and occurred after nightfall. Once fog formed in these simulations, it did not dissipate prior to the simulation ending.

changed to "All of these simulations all ended with a much thinner boundary layer in which height of the inversion lowers by at least 100 m, with the lowering occurring after nightfall. Once fog forms in these simulations, it did not dissipate prior to simulation end."

Line 149: Despite being physically reasonable the gap between

Change to: Despite being physically reasonable, the gap between

changed

Line 153-4: Mean fog duration is calculated with non foggy simulations included with a duration of zero.

Comment: The intent of this sentence is not clear.

Changed to "Mean fog duration is calculated with non-foggy simulations included with a duration of zero and therefore combines the mean duration of fog-producing simulations with the proportion of simulations that produced fog."

The purpose of the sentence is to explain that mean fog duration includes information about the proportion of fog-producing simulations and is distinct from "mean duration of fog" or some other variable that only represents the mean duration of fog that forms.

Figure 3 Caption:

Comment: Explain what (A), (B), (C) mean in the caption. It looks like the variables are the same in (A) and (B). Is (C) average duration difference of the fog that forms relative to the aerosol "base case"?

Figure caption changed to “Relationships between Na and (A) the fraction of simulations that form fog at some time and (B) the mean fog duration including non-foggy simulations averaged over different simulation subsets based on input parameter values. Panel (C) shows the mean duration of foggy simulations with respect to Na for combinations of wsub, Ug, and dTsurf in which the specified number of simulations (continuously starting from the lowest Na) all formed fog.”

Line 185.

Comment: Add the highlighted to sentence:

First, why is it that increasing aerosol leads to increased liquid water path and density of fog at the surface, but decreases the likelihood of fog formation and duration of fog in the model?

added

Line 188.

Comment: Add the highlighted to sentence and explain what thermodynamic represents:

Furthermore, are the model processes that drive the response of fog to aerosol primarily microphysical or thermodynamic?

added "modeled"

Line 195: Add the highlighted to the following:

between fog density and duration with respect to aerosol that differs starkly from the relationship when only external meteorological factors are varied.

added

Line194-5: This is not a surprise, as we would expect meteorological conditions that produce longer-lasting fog to tend towards producing denser fog as well.

Comment: Is there any marine observational evidence of a relationship between fog duration and density?

Changed to “This is not a surprise, as we would expect meteorological conditions that produce longer-lasting fog to tend towards producing denser fog as well within the context of this experiment.”

This comment applies only within this modeling experiment rather than making any claim about fog in nature. The initial temperature and moisture profile is always the same and the simulation stops after 24 hours, so meteorological forcing that favors cloud growth will tend to lead to more rapid fog onset, higher peak fog CWC, and later fog dissipation.

Line 197-198: This contrast suggests that the processes controlling the duration-density relationship for varying aerosol concentration are microphysical rather than thermodynamic.

Comment: Explain what is meant by “thermodynamic”.

Changed to “This contrast suggests that the processes controlling the duration-density relationship for varying aerosol concentration are microphysical rather than thermodynamic, which is to say that the relationship does not act like a forcing condition.”

Line 203+, footnote. If we think of the diurnal cycle as forcing fog onset and dissipation..

Comment: This footnote is not clear and should be removed.

In order to improve clarity, we changed the footnote to “If we think of the diurnal cycle as forcing fog onset and dissipation, then different parts of the day are conducive to fog formation and "densifying" (in this case the first half of the simulation corresponding to afternoon and night), or fog thinning and dissipation (the morning). In a well-mixed layer, the rate at which cloud base lowers prior to fog onset will be proportional to the rate at which cloud becomes denser at a fixed height, and therefore will also be roughly proportional to the rate at which the fog becomes denser after fog onset. This means that when conditions are more favorable to fog, not only will it form earlier, giving it more time to densify before conditions become unfavorable to fog, it will also become denser more rapidly during that time. The combined effect of a longer time during which the fog becomes more dense and a faster rate of densification tells us that peak fog density ought to be roughly proportional to the square of fog duration.”

The purpose of this footnote is to explain why peak fog density is linearly related to the square of fog duration instead of fog duration. We believe that it is important to include an explanation of this, so rather than removing the footnote, we have attempted to improve its clarity.

After Line 203, Figure 4 Caption: CLWC should be changed to CWC

changed

Line 204-5. In fact, there is essentially no relationship between fog duration and density as meteorological conditions are varied for very low Na.

Comment: This should be changed to: In fact, there is essentially no relationship between fog duration and density when meteorological conditions are varied with very low Na.

changed

Line 205+, Figure 5 Caption: CLWC should be changed to CWC. Figure labels (A) and (B) are not used. “R2 values are shown for each Na” should be changed to “ R2 values are shown for each Na listed in figure (A)”. Change “trend lines do a good job of describing” to “trend lines represent well”

changed

Line 207, 5b should be 5A

5b is correct. Figure 5b presents an explanation of the duration-density tradeoff, while 5a expands upon the nature of this relationship. Section 3.3 focuses on the explanation presented in figure 5b while 5a is discussed in section 3.2.

Line 207-208: Here, the x-axis shows the maximum thickness of subsaturated but still cloudy air at the bottom of the cloud during fog.

Comment: I think that this sentence should be rewritten or needs more explanation. Nominally, the fog layer is saturated and extends down to the surface of the ocean or land.

Changed to “In our modeled fog case, fog is sometimes present at the surface when relative humidity is less than 100%. In Figure 5b, the x-axis shows the maximum thickness of the layer of subsaturated air with CWC > 0.01 g/kg (which we define to be “cloudy” air) at the bottom of the cloud during fog.”

Line 208, thickness of subsaturated but still cloudy air,

Comment: should “cloudy air” be “misty air”?

See change made to address previous comment

Line 217: Such considerations then can plausibly explain why fog has a longer duration at low aerosol concentrations

Change to: Such considerations then can plausibly explain why model fog has a longer duration at low aerosol concentrations

changed

Lines 230-245;

Comment: add the word “model” to word “fog” in this area.

added "modeled" in three places

Line 235: Our simulations suggest that this is not typically the case.

Comment: remove “typically”.

done

Line 239: In summary, we see here that meteorological conditions..

Comment: change to “In summary, we see here that model meteorological conditions…”

added "modeled"

Line 247: through a layer of sub-saturated but cloudy air

Comment: change “cloudy” to “misty”

In response to an earlier comment, we specified that we define air with CWC > 0.01 g/kg as “cloudy” for the purposes of this discussion

Line 257: when the aerosol concentration is low

Comment: after low, add “)”

done

Line 258-261: The dominant mechanism by which aerosol concentration impacts entrainment is not important to this study, but the point remains that lower aerosol concentrations and the resulting larger and less-numerous droplets decrease the rate of entrainment and can lead to increased liquid water path.

Comment: Change to: Thus, lower aerosol concentrations and the resulting larger and less-numerous droplets decrease the rate of entrainment and can lead to increased liquid water path.

changed

Line 279: In summary so far, we've seen that microphysical changes..,

Change to: In summary so far, we've seen that model microphysical changes..

added "modeled"

Line 321-322:

Comment: change 1st 2 sentences of paragraph to:

Our study investigates the sensitivity of marine fog formed through cloud base lowering to aerosols under different meteorological conditions using PAFOG, a single column model coupled with a 2-D spectral bin microphysics scheme, MISTRA.

done

Line 328: a substantial layer of subsaturated but cloudy air"

Comment: Suggest change "to "a substantial layer of subsaturated air with visibilities in the range of mist."

changed to "a substantial layer of subsaturated but cloudy (CWC > 0.01 g/kg) air"

Line 320-356: Conclusion

Comment: The conclusion should include a statement summarizing the limitations of the PAROG model and what this possibly means to the key results.

Added "Another potential pitfall is this study's reliance on PAFOG. Though PAFOG has performed well in past studies (Kim and Yum, 2013; Kim et al., 2020b, a; Chen et al., 2021) and demonstrated generally good agreement with other NWP SCMs in the Demistify intercomparison (Boutle et al. (2022)), it is just one model. Experiments using other models could help validate these results, and observational work can aid in the application of these findings to real-world contexts."

Lines 345-355:

Comment: I don't think that this is especially useful and should be removed.

Removed the paragraph, but added "Despite these qualifications, our observation of two competing mechanisms that drive the response to aerosol and multiple fog-aerosol response regimes that can be modulated by meteorological conditions in this *experiment highlights the importance of studying the response of fog to microphysics under a variety of circumstances." to the formerly preceding (now final) paragraph*

Comments from Referee 2 and Associated Responses:

This paper describes the sensitivity of cloud-base lowering fog to microphysical characteristics, particularly the underlying aerosol concentrations. It is very well written and clearly illustrated with relevant figures, leading to simple and well evidenced conclusions. I have no hesitation in recommending for publication. I have only one suggestion that I think would enhance the paper for the reader.

Sect 3 - what is not mentioned here is the influence of radiative changes due to the different aerosol concentrations. With lower aerosol numbers, the larger droplets will also have larger effective radii. This makes the fog layer less absorbing to radiation (short-wave and long-wave), which in turn will make it less emissive. Less absorption in the short wave will tend to promote fog development (less dissipation by the SW heating), while less absorption & emission in the long wave will tend to inhibit fog development (less radiative cooling driving turbulence development at the fog top, see e.g. Boutle et al 2018). In focussing solely on microphysical and thermodynamic mechanisms, these possible effects are not discussed. I think at the very least these mechanisms should be mentioned, but it would also be useful to try to quantify how important radiative effects are on the fog development - are they negligible compared to the microphysical and thermodynamical controls (a general result), or are the radiative effects large but the SW and LW eff ects just happen to cancel in the current simulations making them unimportant?

We addressed this by disabling the optical/radiative properties of aerosol above a height of 480m. The results presented in the original submission are already reflective of this choice. To improve clarity, we have added "Since we are primarily concerned with the microphysical properties of aerosol, the radiative impact of aerosol is disabled above a height of 480 m." to line 134.

L80-85 - could also be worth mentioning the Demistify intercomparison (Boutle et al 2022) here for some background on PAFOG comparison to other models.

We added a statement about the Demistify intercomparison to the conclusion and to this paragraph.

Refs:

Boutle, I., Price, J., Kudzotsa, I., Kokkola, H. and Romakkaniemi, S. (2018). Aerosol-fog interaction and the transition to well-mixed radiation fog. Atmos. Chem. Phys., 18, 7827-7840, doi:10.5194/acp-18-7827-2018

Boutle, I., Angevine, W., Bao, J.-W., Bergot, T., Bhattacharya, R., Bott, A., Duconge, L., Forbes, R., Goecke, T., Grell, E., Hill, A., Igel, A., Kudzotsa, I., Lac, C., Maronga, B., Romakkaniemi, S., Schmidli, J., Schwenkel, J., Steeneveld, G.-J. and Vie, B. (2022). Demistify: a large-eddy simulation (LES) and single-column model (SCM) intercomparison of radiation fog. Atmos. Chem. Phys., 22, 319-333, doi:10.5194/acp-22-319-2022