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Title: Impact of Land Surface Heterogeneity on Mesoscale Atmospheric Dispersion

Article Type: LCLUC Special Issue

Keywords: Atmospheric dispersion; pollution dispersion; effect of landscape heterogeneity on dispersion; air pollution modelling; assessment of adequacy of Gaussian models

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Abstract: Prior numerical modelling studies show that atmospheric dispersion is sensitive to surface heterogeneities. However, past studies do not consider the impact of realistic distribution of surface heterogeneities on mesoscale atmospheric dispersion. While past studies focused on dispersion in the convective boundary layer, the present work also considers dispersion in the nocturnal boundary layer and above. Using a Lagrangian Particle Dispersion Model (LPDM) coupled to the Eulerian Regional Atmospheric Modeling System (RAMS), the impact of topographic, vegetation, and soil moisture heterogeneities on daytime and nighttime atmospheric dispersion is examined in the present study. In addition, sensitivity to the use of satellite-derived, realistic spatial distribution of vegetation characteristics on atmospheric dispersion is also studied.

The impact of vegetation and terrain heterogeneities on atmospheric dispersion is strongly modulated by soil moisture, with the nature of dispersion switching from non-Gaussian to near-Gaussian behaviour for wetter soils (fraction of saturation soil moisture content exceeding 40%). At drier soil moisture conditions, vegetation heterogeneity causes differential heating and formation of mesoscale circulation patterns that are primarily responsible for non-Gaussian dispersion patterns. Nighttime dispersion is very sensitive to topographic, vegetation, soil moisture, and soil type heterogeneity and is distinctly non-Gaussian for heterogeneous land surface conditions. Sensitivity studies show that soil type and vegetation heterogeneities have the most dramatic impact on atmospheric dispersion. To provide more skilful dispersion calculations, we recommend the utilisation of satellite-derived vegetation characteristics coupled with data assimilation techniques that constrain soil-vegetation-atmosphere transfer (SVAT) models to generate realistic spatial distributions of surface energy fluxes.

Suggested Reviewers:

Response to Reviewers: The response to the reviewers is attached as a pdf file. The file had figures, equations, and formatting that would not paste into the text box.

Response to major requested revisions BOUN567

*Note that responses to the editor and the reviewers have been typed under each request in Italic headed with a black dot. Text quoted in the responses is in Times New Roman font.

Response to editor:

Comments from the Co-Editor, John Garratt:

1. Please revise taking into account all comments, queries and suggestions in the two reviews. Editorial and like matters are given below.

2. Editorial issues: authors - please look at a recent issue to familiarize yourself with style and formal requirements of BLM articles.
• *Style and format have been modified to meet BLM requirements.*

a. Keywords - these are missing! Alphabetical order, and first letter of each as upper case.
• *Keywords have been added.*

b. Spelling - european english please: e.g. vapour, modelling, metre, behaviour, etc.
• *Text confirms to European English*.

c. Define all acronyms where possible, otherwise give in full.
• *All acronyms are defined at the first instance of usage*.

d. Use SI units throughout (in roman font).
• *SI units used throughout*.

e. Variables and symbols - all variables should be in italic font. In several places you should use the "approximately equal to" sign, not on the order (~) [which implies to a factor of 3].
• "~" *replaced by* "≈".

f. Equations - Eq.1 should be in three parts, a, b, c, without the left-hand bracket.
Modified as suggested.

g. Times - use 0600, 1230 UTC, etc.
• *UTC time used throughout the text in the suggested format.*

h. References: include total pages (pp.) for all text books and reports. Use appropriate journal abbreviations (for guidance, check "guidelines to authors", and recent issues). E.g., here's some help: Boundary-Layer Meteorol; J Fluid Mech; J Atmos Sci; Mon Weather Rev; Q J Roy Meteorol Soc; J Appl Meteorol, and be consistent.
• *Confirms to specification given in instructions for authors provided at http://boun.edmgr.com/.*

i. Figures - for the amount of discussion there are too many, particularly since many are very detailed. Please reduce from 11 to 8 if possible.

• *Authors feel that the figures used in the manuscript are necessary to adequately describe the results which are based on three experiment sets with multiple releases.*

3. When submitting your revised article, include a set of detailed responses to all points in the two reviews, and show how you have revised the text in each instant. Check all cited literature against the reference list. The revised article may go back to ref 1 for re-evaluation.

Response to Reviewer #1:

Reviewer #1: Comments on the manuscript BOUN567 entitled "Impact of Land Surface Heterogeneity on Mesoscale Atmospheric Dispersion" by Y. Wu, U. S. Nair, R. A. Pielke Sr, R. McNider, S. A. Christopher and V. Anantharaj.

This paper primarily describes about the impact of land-surface characteristics on mesoscale atmospheric dispersion. The authors have carried out an extensive study using different aspects of land-surface heterogeneity including soil properties. This paper provides an insight to the use of three dimensional numerical mesoscale models coupled with a lagrangian particle dispersion model in the study of mesoscale dispersion pattern. The most important aspect of the study is the impact of underlying land-surface heterogeneity on mesoscale dispersion of air pollutants. It is really a nice effort by the authors to put together the concerns of heterogeneous land-surface and mesoscale dispersion. However, I have following concerns and they need to be addressed before publication.

General comments:

1. The title "Study Objectives..." can be merged with title "Introduction". This will help to make the introduction much more precise and short.
• *Sections merged into a single new section titled "Introduction"* .

2. In the manuscript a number of abbreviations are not defined such as THOM, VHOM, TVHOM, HET1, HET2, NDVI and NAM on pages 7 and 8.

• *Abbreviations (NDVI, NAM, etc) defined at the first instance of their use. The following underlined text inserted in the sentence in section 2.3 where the first reference to acronyms used to denote numerical experiments occurs: "Experiments S1-S5 (defined Table 1 along with acronyms for all other experiments) are utilised to understand the role of soil moisture in modulating the impact of vegetation heterogeneity on dispersion"* .

3. The figures can be improved. Please look the specific comments for this.

Specific comments:

ABSTRACT
Page 1 line 8 in the first paragraph: Add "in the present study" after the word "examined". Add "In addition," before the word "sensitivity".
• *Modified as suggested.*

Page 1 in the second paragraph line 7 from the bottom: replace "and" by "," after the word "vegetation".
• *Modified as suggested.*

Page 1, second paragraph: Define "SVAT"

• *It's now "...with data assimilation techniques that constrain soil-vegetation-atmosphere transfer (SVAT)"*

INTRODUCTION

Page 2, third paragraph line 8 from the bottom: delete "however", "even" and "but"

• *Modified as suggested.*

Page 2, third paragraph: The line "This circulation was documented for ....data" is redundant. Delete this statement.

• *Modified as suggested.*

Page 3 first paragraph: The statement However, even....pollution (e.g. Whiteman 1982; Pielke 1985)" need to be shifted to the end of previous paragraph.

• *Paragraph modified as follows and shifted to the end of the previous paragraph: "However, even more serious errors can result with non-flat heterogeneous landscapes. When terrain is present, for instance, dispersion can be reduced significantly since air can recirculate multiple times with a resultant accumulation of pollution (e.g., Whiteman 1982; Pielke 1985). In deep valleys, where pollution is not able to exit, concentrations can become quite large (e.g., see McNider and Pielke 1984; Pielke et al. 1986; Wolyn and McKee 1989) due to stagnation and is not captured by Gaussian models. Inadequacies of Gaussian models in accounting for atmospheric dispersion features caused by landscape heterogeneity are further discussed in Pielke and Uliasz (1998) and Pielke (2006)".*

Page 3 second paragraph: This sentence is redundant. Please reconstruct the sentence and shift it to the earlier paragraph at the end.

• *Sentence has been reconstructed and shifted to the previous paragraph: "Inadequacies of Gaussian models in accounting for atmospheric dispersion features caused by landscape heterogeneity are further discussed in Pielke and Uliasz (1998) and Pielke (2006)".*

STUDY OBJECTIVES AND ANALYSIS FRAMEWORK

Page 3 in the first paragraph of this section: Define "p".

• *Modified as "...t* is time travelled, and, the <u>exponent of t has the constraint</u> $1 \geq p \geq \frac{1}{2}$"

Page 4 line 2: Define "LES"

• *Modified as "...at small spatial scales by using <u>large eddy simulation</u> (LES) experiments."*

Page 4 in the first paragraph line 12: Replace "Thus" BY "In this case".

• *Modified as suggested*

Page 4 last line: Add "mechanism" after "control"

• *The whole sentence revised from "At night time, mechanically-generated turbulence becomes the more dominant control on turbulent dispersion." to "At nighttime, mechanically-generated turbulence as well as the suppression of turbulence by increased vertical thermodynamic stratification due to long-wave radiative flux divergence, become the more dominant control effects on turbulent dispersion."*

Page 5 at the beginning: Reconstruct the statement "Mesoscale circulation features...".This does not convey the appropriate intension.

• *Reworded as: "Mesoscale circulation features become a dominating factor at regional scales, especially those with dimensions comparable to that of the plume".*

Page 5 the last paragraph of this section: Replace "differing" by "different" in the last statement.
• *Modified as suggested.*

DESCRIPTION OF RAMS
Page 6: The first statement is a repetition. Delete the first statement.
• *Modified as suggested.*

Page 6: In the last line of this section, add "also" before "available"
• *Modified as suggested.*

DESCRIPTION OF THE LPDM
Page 7: Give a reference for the Markov process.
• *"Markov process" has been omitted from The sentence and it now read as "The subgrid-scale components are modelled using linear Langevin stochastic differential equations (e.g., Gifford 1982)"*

NUMERICAL MODEL EXPERIMENTS
Page 7: Change the title to "Experimental Design"
• *Modified as suggested.*

Page 8 line 10: Add "and" after the word "model experiment" in the second paragraph
• *Modified as "LAI is directly utilised in the model experiment, <u>with fractional</u> vegetation derived..."*

Page 8: Reconstruct the last sentence of second paragraph
• *Modified as: "Vegetation albedo is determined from the MODIS satellite derived total albedo by utilising fractional vegetation derived from NDVI along with the albedo of bare soil parameterised as a function of soil moisture."*

Page 8: In the last paragraph the authors describe about the domain referring to figure 1. However, the details of the domain are not clear from figure 1. I would suggest showing the domain with map, points of release etc in a separate figure.

- *Modified as suggested.*

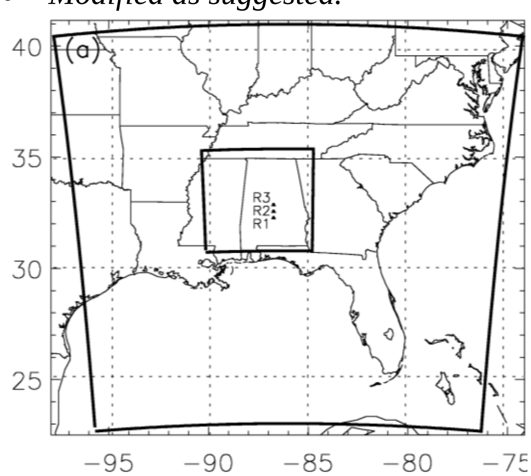


Fig. 1 *(a) The two nested grid domains of the simulation are drawn in bold lines and the release sources are indicated by the triangle symbols.*

Page 8: In the last paragraph the authors describe about the stretching of grid and vertical levels. However, the statements do not clearly represent what needs to be conveyed.

- *Modified as: "A stretched grid with 56 grid points and stretch ratio of 1.1 was applied in the vertical direction resulting in the grid spacing gradually increasing from 20 m near the surface to a maximum of 500 m at an attitude of 4.91 km. Above 4.91 km the grid spacing remains at 500m till domain top at 15.41 km."*

Page 8 line 4 from bottom: Define NAM. Add "of" before the words "the experiments"

- *Modified as suggested.*

Page 8 line 2: Add "of" before the words "the experiments"

- *Modified as suggested.*

Page 8: In the last paragraph, the authors describe about the vertical diffusion scheme. Is there any need of extra vertical diffusion scheme? Is the boundary layer scheme not taking care of the vertical diffusion?

- *The Mellor-Yamada scheme is the boundary layer scheme. Text modified to state "In the application of RAMS for this study, the Mellor-Yamada turbulence parameterization is utilised for vertical diffusion" instead of "Simulations utilise the Mellor-Yamada diffusion scheme in the vertical" to avoid confusion. Note that horizontal and vertical diffusions are simulated separately in RAMS.*

Page 9: In the last paragraph the authors have mentioned LEAF-2 parameterization. Please explain this as it is not clear from the text.

- *LEAF-2 is a SVAT model within RAMS that accounts for land-atmosphere interactions. Note that section 2.1 provides a brief description and appropriate citation for this model. Referring to LEAF-2 as a parameterization in section 2.3 opposed to a submodel in section 2.1 may have contributed to some confusion. The sentence is modified as follows: "The LEAF-2 <u>SVAT model</u> (see section 2.1) within RAMS assigns values for these variables based on vegetation type (Figure 2a, 2c, and 2e) and does not show significant variation within each class."*

RESULTS

Page 10: The authors describe about figure 1 showing topography, vegetation and soil texture etc. It does not show the point of releases. There should be a paragraph and proper diagram describing the point of releases.

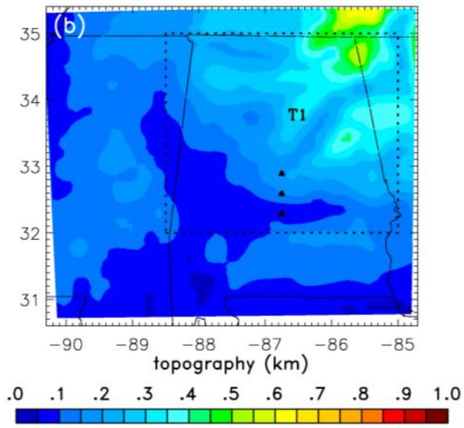
- *The point of releases are marked by small triangles in the figure and indicated in the last sentence of the figure caption: "the three little triangles, R1, R2, and R3 mark the release sources locations"*

Page 11: In the sub-section 4.1 last statement of second paragraph add "through" before the word "distances".

- *Modified as suggested*

Page 12: The authors talk about topographic ridge T1. Where is T1? It is not clear from the figure 1a.

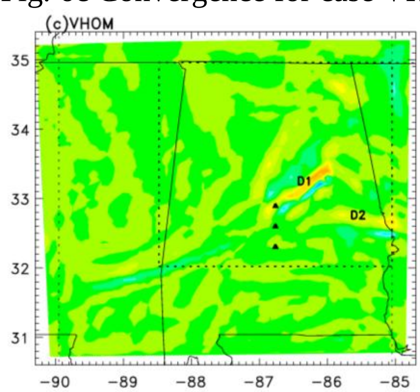
- *New Fig. 1b(re-numbered) with T1 marked is now:*



Page 12: The description about flow features talk about divergence and convergence. Will it be possible to draw the wind vectors for this? It may clearly show what the authors want to convey.

- **To limit the number of figures we choose to show only the div/conv field plot for the reason that particles follow the flow and their movement shows the temporal and spatial evolution of the flow.*

Page 14: In the top of this page the authors talk about D1 and D2 features. What are these? They are not clear from the figure 6c.

- Fig. 6c Convergence for case VHOM with D1 and D2 marked:
- 

Page 15 line 9: Replace the word "extent of" by "within".

- *Modified as suggested*

Page 17: In the last paragraph the authors talk about Alabama-Mississippi border in different experiments. It is not clear from the figure unless Alabama is represented in the figure by drawing the map.

- *We have revised the plots of particle dispersion and color the state border line on the map with a brief description indicating the states. Take Fig. 4 for example:*

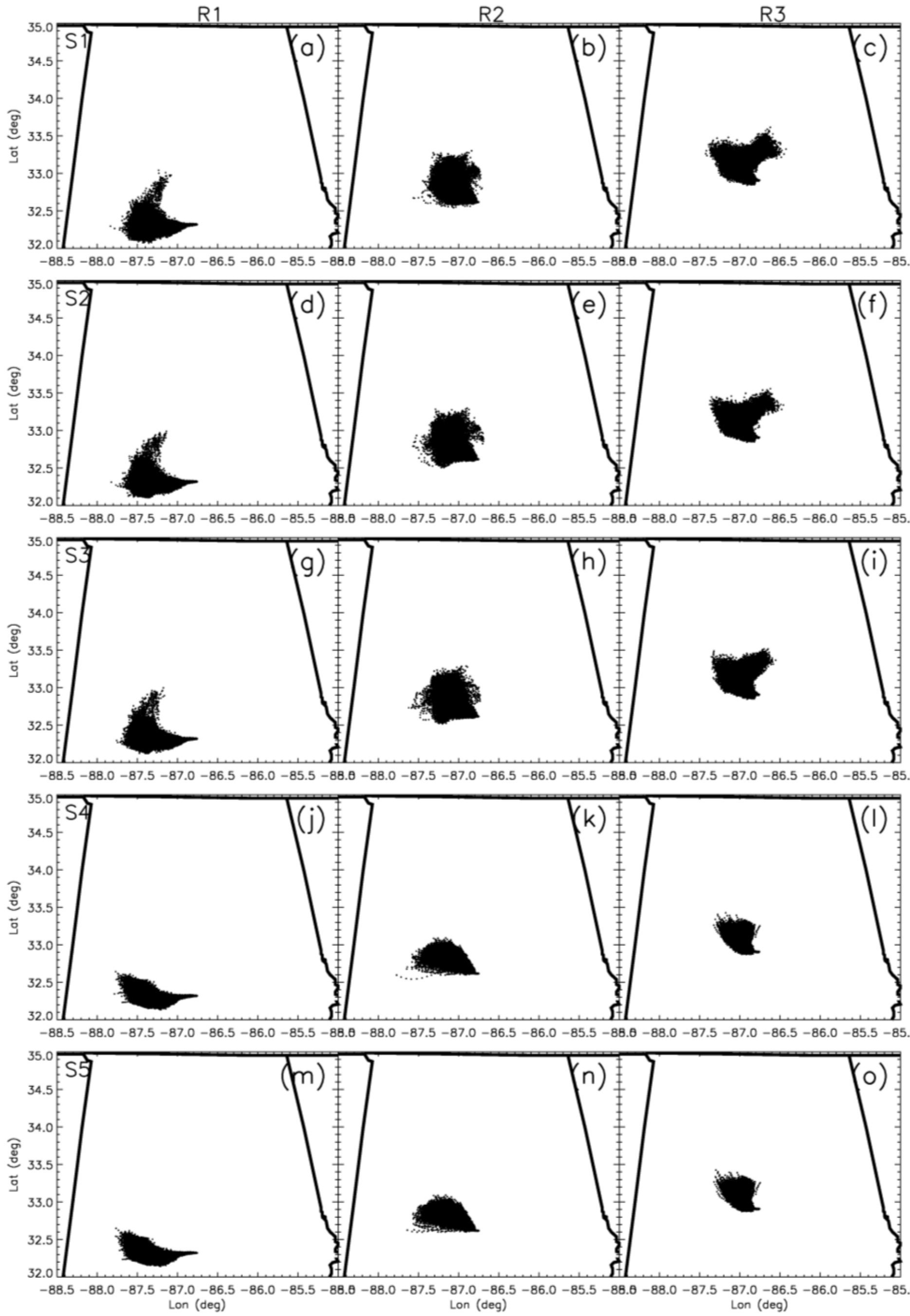


Fig. 4 *The 12 hour (12-24 UTC, May 21, 2007), daytime dispersion patterns for R1-R3 releases for S1, S2, S3, S4, and S5 experiments are shown in panels a-c, d-f, g-i, j-l, and m-o respectively. The bold black line indicates the Alabama state borders. The states of Mississippi, Tennessee, and Georgia are to the west, north, and east of Alabama respectively.*

Page 18 line 10 from bottom: Add "as" before the word "compared"

- *Modified as suggested"*

Page 18: In the last paragraph the authors describe about mesoscale circulation features by mentioning figure 11. Will it be possible to draw wind vectors?

- *See previous response marked by asterisk for page 12.*

DISCUSSION

Page 19: In the last paragraph the authors talk about SVAT models in WRF. Can you give an example?

- *An example of a SVAT model in WRF is the NoahLSM. However, we have omitted that part to keep focus on RAMS. The sentence was modified as follows: "Atmospheric models, such as RAMS, use SVAT models (LEAF-2) to parameterise land-atmospheric interactions."*

Page 20: In the last paragraph, the authors emphasize upon data assimilation technique and discuss about its importance. However, as I understand they are not using this in this work. I feel this should not be emphasized too much in the text if they are not using this technique.

- *Even though the present study does not utilize data assimilation techniques, results from the sensitivity analysis suggest that improvement in representation of soil moisture heterogeneity is important. The authors consider the data assimilation technique important and can be a big improvement to make up the insufficient representation of soil moisture field for the simulation if applied. The intention was to state that there's room for improvement in getting more realistic soil moisture field and give a hint for future work.*

CONCLUSION

Page 22: In the fourth conclusion, please replace "topographic, vegetation, soil moisture and soil type heterogeneity" by heterogeneity in topography, vegetation, soil moisture and soil type.

- *Modified as suggested.*

Page 22: In conclusion no-5 add "of" before the word "satellite-derived".

- *Modified as suggested*

Page 22: I think the conclusion no-6 is not a finding from the study. So, do not include in the number of findings. Reconstruct the statements. Make it a separate paragraph in the last and combine with the last paragraph.

- *We have moved it from the numbered findings, and leave it at the end.*

REFERENCES

Please check the consistency of the references along with the format of Boundary Layer Meteorology. The names of the journals are italicized at some places where as not at others. At some places, the volume numbers are made bold and at some others it is not. I would recommend to go through the references critically and make it as desired by the journal.

- *Consistency has been checked.*

FIGURE CAPTIONS

Make the complete text uniform. At some places the words are bold. Write either May 21 or May 21st. Write either May 22 or May 22nd. Use either UTC or GMT throughout.

- *We now use the format of "May 21" and UTC throughout.*

TABLES

Page 32: I think the authors have carried out experiments S1-S5. There is not any experiment called "S6"

- *The experiments are indeed S1-S5. It has been modified.*

FIGURES:

Include one figure showing the detailed graph of the domain and point of releases etc. Use either UTC or GMT.

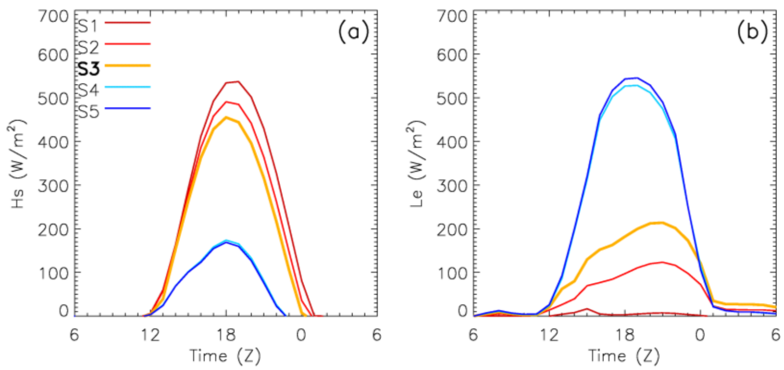
- *Modified as suggested.*

Fig 2: What is vegetation albedo? Is it same as that of albedo or different?

- *Vegetation albedo is different from albedo ("total albedo" as we call it). The total albedo includes the albedo effects from vegetation and soil. We have changed "vegetation albedo" to "albedo of vegetation" in the text to avoid confusion.*

Fig 3: Improve this figure.

- *Improved with legend added.*



Response to Reviewer #2:

Reviewer #2: General Comments:

Overall, the paper presents a valuable modeling study that would be of great interests to the larger community. The paper clearly describes the importance of spatial heterogeneity in soil and vegetation characteristics on atmospheric dispersion. However, while the paper is well written with the methods, conclusions, and relevancy of the work well described, there are some important corrections and revisions needed. (These are enumerated below.) I would recommend the acceptance of the paper be contingent on these revisions.

Specific Comments:

Page 2, Line 6: The word "however" is not necessary.

- *Modified as suggested.*

Page 2, Line 15: The sentence beginning, "When mesoscale circulations." Is unclear and should be revised.

- *Reworded as: "When mesoscale circulations occur over flat terrain with heterogeneous landscapes, the recirculation of pollution can result in its accumulation over time."*

Page 3, Line 8: A word is missing after "detailed".

- *The whole sentence has been reworded as follows: "Inadequacies of Gaussian models in accounting for atmospheric dispersion features caused by landscape heterogeneity are further discussed in Pielke and Uliasz (1998) and Pielke (2006)."*

Page 3, Line 10: It would be nice to include a brief outline of how the paper is laid out.

- *The last paragraph in the introduction section was modified as follows: "The overall goal of this study is to assess the effect of real world heterogeneity on atmospheric dispersion by extending the analysis of Gopalakrishnan et al. (2000) and Gopalakrishan and Avissar (2000) to regional scales. In specific, this study focuses on the following aspects of the land surface heterogeneity and topographical forcing impacts on atmospheric dispersion: 1) Relative roles of land surface heterogeneities (land use, soil type variations) and topographical forcing; 2) Role of soil moisture in modulating the impact of land surface heterogeneities. Numerical experiments designed to isolate the effect of these different forcing factors will be applied in this study. The remainder of the paper first describes the methodology used in this study (section 2), followed by results (section 3), a discussion of the findings (section 4), and finally the conclusions are summarised (section 5)."*

Page 3-5: The authors states in the opening of each paragraph of this section the main objective of the study is. and each time gives a slightly different goal for this work. I would suggest they redraft this section of this paper to state clearly what the objective of this work is and why it is important. The other goals could then be discussed in that context.

- *The last paragraph in the introduction section reworked to address the concern of the reviewer. Please refer to the response to the previous comment.*

Page 5, Line 14: While introductory paragraphs are helpful in understanding the full context of the methodology section, this paragraph provides little in the way of an overview.

Page 6, Line 2: This sentence is lifted word-for-word from the previous paragraph.

Page 6, Line 2-13: While the overview of RAMS is helpful. How were the different options set for this simulation study? I see this information follows on pages 8-9. You should consolidate these sections.

- *In order to address the above three reviewer comments, the Methodology section has been revised, re-constructed, and consolidated.*

Page 7 and Table 1: Are these soil moisture fractions, the soil moisture content or the fraction of saturation soil moisture content? I suspect the latter, but this needs to be clarified.

Page 9, Line 14: Please define soil saturation as you are using it here. I think you are defining it as a percentage of field capacity or saturation soil moisture content, but this is unclear.

- *They are the fraction of saturation soil moisture content. The text is now "$\approx$0.24 m^3/m^3, $\approx$50% fraction of saturation soil moisture content, called "soil saturation" hereafter"*

Page 10, Line 14: The information regarding releases should be included in the methodology section. Also, additional information is needed to describe each of these releases and how they differ.

- *Added the following short paragraph in the methodology section: In order to determine the impact of land surface heterogeneity on atmospheric dispersion, LPDM simulates particles released from three locations (see R1, R2 and R3 in Figure 1) for all the experiments described in Table 1. The release locations are chosen to sample regions of significant topographical (R3) and land surface heterogeneity (R1 – soil texture heterogeneity, R2- land use heterogeneity), so that the plumes from these release locations experience different transport and dispersion due to the local flow affected by the heterogeneous topography or surface sensible heat fluxes, or both.*

Page 10, Line 22: Following "transpiration" the parenthetical "sensible heat flux" is confusing. Separate this out as a separate sentence.

- *It is revised as "and transpiration increases approximately in proportion to the variation in soil saturation, while the sensible heat flux decreases."*

Page 11, Line 1-8: These results are not altogether unexpected given the simulations are transitioning from a water-limited regime to an energy-limited one. The authors should discuss this in the paper.

Page 11, Line 9-15: Again, this is expected given the reduced sensible heat flux and convective turbulence with higher soil moisture.

- *While the simulations are transitioning from a water (latent heat flux)-limited regime to an energy (sensible heat flux)-limited one, our point, as stated at the very beginning of the paragraph, is also on the non-linear response of energy partition, not only on the transition.*

Page 22, Line 8: How is this conclusion regarding the nocturnal boundary layer different from the more generalized case?

- *One would expect the nocturnal plumes to stay narrow because of the stable stratification condition and lower turbulent dispersion as compared to that in the daytime CBL.*

Fig. 3: A legend is needed for this plot. I assume that the blue lines are wetter and the red lines are dry, but this needs to be explicit.

- *Legend added to the plot to indicate the case each line represents. The blue lines are wetter and red lines are drier.*

3

Impact of Land Surface Heterogeneity on Mesoscale Atmospheric Dispersion

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ABSTRACT

Prior numerical modelling studies show that atmospheric dispersion is sensitive to surface heterogeneities. However, past studies do not consider the impact of realistic distribution of surface heterogeneities on mesoscale atmospheric dispersion. While past studies focused on dispersion in the convective boundary layer, the present work also considers dispersion in the nocturnal boundary layer and above. Using a Lagrangian Particle Dispersion Model (LPDM) coupled to the Eulerian Regional Atmospheric Modeling System (RAMS), the impact of topographic, vegetation, and soil moisture heterogeneities on daytime and nighttime atmospheric dispersion is examined in the present study. In addition, sensitivity to the use of satellite-derived, realistic spatial distribution of vegetation characteristics on atmospheric dispersion is also studied.

The impact of vegetation and terrain heterogeneities on atmospheric dispersion is strongly modulated by soil moisture, with the nature of dispersion switching from non-Gaussian to near-Gaussian behaviour for wetter soils (fraction of saturation soil moisture content exceeding 40%). At drier soil moisture conditions, vegetation heterogeneity causes differential heating and formation of mesoscale circulation patterns that are primarily responsible for non-Gaussian dispersion patterns. Nighttime dispersion is very sensitive to topographic, vegetation, soil moisture, and soil type heterogeneity and is distinctly non-Gaussian for heterogeneous land surface conditions. Sensitivity studies show that soil type and vegetation heterogeneities have the most dramatic impact on atmospheric dispersion. To provide more skilful dispersion calculations, we recommend the utilisation of satellite-derived vegetation characteristics coupled with data assimilation techniques that constrain soil-vegetation-atmosphere transfer (SVAT) models to generate realistic spatial distributions of surface energy fluxes.

1 Introduction

The modelling of the dispersion of pollution and other effluent into the atmosphere has generally relied on Gaussian puff and plume modelling (e.g., see Zannetti 1990). As discussed in Pielke (1984), the American Meteorological Society's position paper states that "*over flat, horizontally homogeneous terrain, Gaussian plume models probably give estimates of downwind plume concentrations within a factor of two.*"

One of the errors associated with Gaussian models is that they cannot properly represent the combined effect of differential vertical and horizontal advection and turbulent diffusion which together yield *dispersion* (Lyons et al. 1995). The actual mixing of the pollution from the differential advection can also be delayed until turbulent transfers occur across vertical and horizontal distances (McNider et al. 1988; Moran 1992; Moran and Pielke 1996; Poulos and Pielke 1994). As shown in Eastman et al. (1995) and Pielke and Uliasz (1993), without the occurrence of the recirculation of effluent, dispersion is generally enhanced for heterogeneous flat landscapes as compared to homogenous landscapes over flat terrain although the importance of the heterogeneity becomes less as the wind speed increases and/or the heterogeneity is of smaller spatial scale.

When mesoscale circulations occur over flat terrain with heterogeneous landscapes, the recirculation of pollution can result in its accumulation over time. Eastman et al. (1995) found for a lake breeze circulation along the coast of Lake Michigan that about 70% of the pollution recirculated at least once. A Gaussian model, even with a set of vertical connected plumes (e.g., discussed in Zannetti 1990), cannot represent this recirculation. The presence or absence of snow on the ground can also greatly affect the dispersion of pollution (Segal et al. 1991). However, even more serious errors can result with non-flat heterogeneous landscapes. When terrain is present, for instance, dispersion can be reduced significantly since air can recirculate multiple times with a resultant accumulation of pollution (e.g., Pielke 1985; Whiteman 1982). In deep valleys, where pollution is not able to exit, concentrations can become quite large (e.g., see McNider and Pielke 1984; Pielke et al. 1986; Wolyn and McKee 1989) due to stagnation and is not captured by Gaussian models. Inadequacies of Gaussian models in accounting for atmospheric dispersion features caused by landscape heterogeneity are further discussed in Pielke (2006) and Pielke and Uliasz (1998)

The primary objective of this study is to assess the effect of real world land surface heterogeneity on dispersion. Gaussian dispersion models based on Taylor's theory ($\sigma \propto t^p$, where σ is the plume spread, t is time travelled, and the exponent of t has the constraint $1 \geq p \geq \frac{1}{2}$) are only adequate for turbulent dispersion near the source or for uniform flows. Inhomogeneities in flow fields may be addressed to a certain extent by utilising a wind shear factor. For long-range transport, mesoscale circulation features that are comparable in dimension to the plume, can distort the plume in a manner that is significantly different when compared to predictions using classical theories. Lagrangian Particle Dispersion Models (LPDMs), driven using output from Eulerian meteorological models provide a more realistic representation of plume dispersion within inhomogeneous flow fields. However, the performance of LPDMs is tied to the ability of the meteorological model to capture flow features at scales in consideration.

Gopalakrishnan and Avissar (2000) and Gopalakrishnan et al. (2000) examined the impact of land surface heterogeneity at small spatial scales by using large eddy simulations (LES) experiments. Gopalakrishnan et al. (2000) studied the role of topography on atmospheric dispersion by imposing sinusoidal topographical features in LES simulations and found that at scales greater than 5 km, topography significantly impacts horizontal and vertical velocity variances. Even smaller-scale terrain features have a substantial effect (e.g., see Hadfield et al. 1991, 1992). However, the impact of topography is dependent on the surface sensible heat flux with the response diminishing with increasing surface heat flux. Gopalakrishnan and Avissar (2000) imposed heterogeneous distributions of heat flux, in the form of a sinusoidal wave, in LES simulations and found a significant impact on dispersion in the convective boundary layer (CBL). Imposition of heterogeneous fluxes resulted in the formation of roll circulations that impeded vertical mixing. In this case tracers released near the surface dispersed more in the horizontal direction and elevated releases took longer to reach the surface compared to homogeneous surface flux conditions (Gopalakrishnan and Avissar 2000). However, the simulations imposed an initial shear-free wind profile, and the results could be significantly different in the presence of even modest wind shear.

In LES simulations of the CBL, the near-source dispersion is dominated by subgrid scale, thermally-generated turbulence while far from the source, the effect of larger eddies become important. At nighttime, mechanically-generated turbulence as well as the suppression of turbulence by increased vertical thermodynamic stratification due to longwave radiative flux divergence, become the more dominant control effects on turbulent dispersion. At regional scales, dispersion is influenced by mesoscale circulation features generated by differential heating, topographical forcing, and mechanical interactions resulting from spatial variations in surface roughness. Mesoscale circulation features become a dominating factor at regional scales, especially those with dimensions comparable to that of the plume. Soil moisture also plays an important role in modulating the nature of surface sensible flux heterogeneity and thus regional-scale dispersion (Eastman et al. 1998; Ookouchi et al. 1984).

The overall goal of this study is to assess the effect of real world heterogeneity on atmospheric dispersion by extending the analysis of Gopalakrishnan et al. (2000) and Gopalakrishan and Avissar (2000) to regional scales. In specific, this study focuses on the following aspects of the land surface heterogeneity and topographical forcing impacts on atmospheric dispersion: 1) The relative roles of land surface heterogeneities (land use, soil type variations) and topographical forcing; and 2) The role of soil moisture in modulating the impact of land surface heterogeneities.. Numerical experiments designed to isolate the effect of these different forcing factors will be applied in this study. The remainder of the paper first describes the methodology used in this study (section 2), followed by results (section 3), a discussion of the findings (section 4), and finally the conclusions are summarised (section 5).

2 Methodology

This study utilises a Lagrangian particle dispersion model (LPDM) embedded within the Regional Atmospheric Modeling System (RAMS, Version 4.4) to study the impact of land surface heterogeneity on atmospheric dispersion. The LPDM is directly embedded in the meteorological model so that the near instant wind field is used to drive particle dispersion. The LPDM is based on McNider (1981) which has been used to simulate long-range, mesoscale plume dispersion (Gupta et al. 1997; McNider et al. 1988, 1993).

2.1 Description of the Regional Atmospheric Modeling System (RAMS)

RAMS is a nonhydrostatic atmospheric model that utilises finite difference approximations to solve the conservation equations of mass, momentum, heat, and different water phases and has been successfully used to simulate a wide range of atmospheric phenomenon (Cotton et al. 2002). Convective parameterisation and explicit parameterisation of cloud microphysics are options within RAMS for representing cloud and precipitation processes. Options with varying sophistication are also available within RAMS for representing subgrid-scale turbulence. The Land Ecosystem Atmosphere Feedback (LEAF-2) model (Walko et al. 2000), the soil-vegetation-atmosphere transfer (SVAT) component within RAMS, account for vertical momentum, energy, and moisture transfers between the atmosphere and land. Radiative transfer schemes of varying complexity are available in RAMS (Chen and Cotton 1983; Harrington et al. 1999; Mahrer and Pielke 1977) .

In the application of RAMS for this study, the Mellor-Yamada turbulence parameterisation is utilised for vertical diffusion, while a modified Smagorinsky deformation scheme is applied in the horizontal. The Kuo convective parameterisation along with cloud microphysical parameterisation was utilised to represent cloud and precipitation processes. The radiative transfer scheme of Harrington et al. (1999) was used to account for radiative transfer processes. Aerosol effects have been ignored in these experiments.

2.2 Description of the LPDM

The particle plume dynamics model employed in the current study is adapted from the model developed by McNider (1981) and McNider et al. (1988). The model has been used to study long-range plume transport (McNider et al. 1988), the wind shear effect produced by inertial oscillation (McNider et al. 1993), and the energy spectrum in mesoscale plume transport (Gupta et al. 1997). In general, for particles released in an Eulerian frame, the displacement can be expressed by:

$$x(t+\Delta t) = x(t) + [\bar{u}(x,y,z,t) + u'(x,y,z,t)]\Delta t, \tag{1a}$$

$$y(t+\Delta t) = y(t) + [\overline{v}(x,y,z,t) + v'(x,y,z,t)]\Delta t, \quad (1b)$$

$$z(t+\Delta t) = z(t) + [\overline{w}(x,y,z,t) + w'(x,y,z,t) + w_d]\Delta t, \quad (1c)$$

where overbars denote the mean quantities including the meso- and larger-scale variation, primes denote the fluctuations from the mean quantities representing the subgrid velocities, and w_d is a drift correction velocity introduced by Legg and Raupach (1982) to avoid the accumulation of particles toward the lower energy in the vertically inhomogeneous flow. The subgrid-scale components are modelled using linear Langevin stochastic differential equations (e.g., Gifford 1982) with the turbulent quantities parameterised for different stability conditions. The drift correction velocity, w_d, uses the following formulation of Legg and Raupach (1982):

$$w_d = T_w \frac{\partial \sigma_w^2}{\partial z} [1 - exp(-\Delta t / T_w)]. \quad (2)$$

2.3 Experimental Design

This study uses a set of simulations with identical initial atmospheric conditions, but varying lower boundary conditions to isolate the impact of a spatially heterogeneous distribution of topography and surface sensible heat fluxes on atmospheric dispersion and also the modulation of the surface sensible heat flux heterogeneity effect by soil moisture (Table 1). Experiments S1-S5 (defined in Table 1 along with acronyms for all other experiments) are utilised to understand the role of soil moisture in modulating the impact of vegetation heterogeneity on dispersion. Experiments THOM and VHOM are aimed at isolating the impact of terrain and vegetation heterogeneities on atmospheric dispersion by comparing against S3, whereas experiment TVHOM is used for examining the combined impact of terrain and vegetation inhomogeneities. The HET1 and HET2 experiments include topographic, vegetation, and soil moisture heterogeneities, with the HET2 experiment differing from the HET1 experiment in the use of MODIS satellite derived vegetation characteristics to constrain vegetation heterogeneity. The HET3 and HET4 experiments are similar to the HET1 and HET2 experiments, except for the use of a heterogeneous distribution of soil type. The HET3 and HET4 experiments are utilised to examine the overall impact of land surface heterogeneity on atmospheric dispersion, while the difference between the HET3, HET4, and the HET1, HET2 experiments are used to isolate the impact of soil type heterogeneity.

The vegetation characteristic, Leaf Area Index (LAI), Vegetation Fraction (VF), and Vegetation Albedo (VA), utilised in the HET2 and HET4 experiments are derived from the following MODIS land products: Normalised Difference Vegetation Index (NDVI, MOD13A2 dataset), Leaf Area Index (LAI, from MOD15A2 dataset, Myneni et al. 2002) and broadband albedo product (MOD43B3, Schaaf et al. 2002). LAI is directly utilised in the model experiment, with fractional vegetation derived from the NDVI product using the method of Carlson and Ripley (1997). Vegetation albedo is determined from the MODIS satellite-derived total albedo by utilising factional vegetation derived from NDVI along with the albedo of bare soil parameterised as a function of soil moisture.

Two nested grids of RAMS configuration (see Figure 1a) were used in all the experiments. The outer grid consists of 101 × 101 grid points covering the southeast US with a grid spacing of 20 km in both x and y directions. The inner grid with the model domain of 52 × 52 grid points covers a study area consisting of Alabama, parts of Tennessee, Mississippi, and Georgia. A grid spacing of 10 km is used in both x and y directions. A stretched grid with 56 grid points and stretch ratio of 1.1 was applied in the vertical direction resulting in the grid spacing gradually increasing from 20 m near the surface to a maximum of 500 m at an attitude of 4.91 km. Above 4.91 km the grid spacing remains at 500 m till domain top at 15.41 km. Eight soil levels, located at 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, and 2 m depths were used in all of the experiments. The North American Model (NAM) atmospheric analysis of National Centers for Environmental Prediction (NCEP) was used to nudge the lateral boundaries of the outer grid and a nudging time scale of 7200 s was utilised in all of the experiments.

Moderate terrain variations, associated with the Smoky Mountain and its extension into Northern Alabama, are found in the northeast part of the experimental domain (Figure 1b). The spatial distribution of vegetation type shows deciduous broadleaf vegetation dominating the northern part of the domain with evergreen needleleaf vegetation occupying the southern and central regions (Figure 1c). Significant areas of crop/mixed farming land-use type are also found in the central and southeastern regions of the domain, while small urban/built-up locations are distributed throughout the domain (Figure 1c). The soil type (Figure 1d) over the study area consists of silt loam in the southern, central, and northern parts of Alabama and silty clay loam covering the rest of the region. The NAM-derived soil moisture field, used to specify soil moisture heterogeneity in experiments HET1, HET2, HET3, and HET4, show relatively wet conditions throughout most of the domain (≈ 0.24 m^3/m^3, $\approx 50\%$ fraction of saturation soil moisture content, called “soil saturation” hereafter) except in the southeastern part of the domain and in small pockets of northern Alabama (Figure 1e). Sandy clay loam, the uniform soil type assumed in experiments S1-S5, and HET1 and HET2, is chosen since its hydraulic conductivity is approximately intermediate between that of silt loam and silty clay loam, the major soil types in the study area.

Note that in order to obtain a complete picture of the spatial heterogeneity associated with vegetation, other characteristics such as LAI, VF, and VA also need to be considered (Figure 2). The LEAF-2 SVAT model (see section 2.1) within RAMS assigns values for these variables based on vegetation type (Figure 2a, 2c, and 2e) and does not show significant variation within each class. Spatial variations in the VF and VA field specified in LEAF-2 mirrors vegetation type, while the LAI field shows only very minor variations in the northern part of the domain. However, the MODIS satellite-derived fields for these variables (Figure 2b, 2d, and 2f) show significant spatial variations within the same vegetation type. Thus the use of satellite-derived vegetation fields better captures the nature of land surface heterogeneity associated with vegetation.

In order to determine the impact of land surface heterogeneity on atmospheric dispersion, LPDM simulates particles released from three locations (see R1, R2, and R3 in Figure 1) for all the experiments described in Table 1. The release locations are chosen to sample regions of significant topographical (R3) and land surface heterogeneity (R1 – soil texture heterogeneity, R2- land use heterogeneity), so that the plumes from these release locations experience different transport and dispersion due to the local flow affected by the heterogeneous topography or surface sensible heat fluxes, or both.

Note that the Gulf States in the southern US are often impacted by mesoscale transport of smoke from biomass burning in Central America during the spring and early summer season. During the time period considered in this study (May 21-22, 2007), smoke from forest fires in Florida was transported over the subject area. While this study does not consider comparison against the observed smoke event, conditions during this time period are still representative of mesoscale transport events in this region.

3 Results

Dispersion patterns associated with releases from three locations (Figure 1) are compared for the different experiments. Release locations are chosen to sample regions of significant topographical (R3) and vegetation (R1 & R2) heterogeneity. Releases are initiated at 12 UTC and maintained for 18 hours. The dispersion patterns were analysed in the convective boundary layer during the first 12 hours and in and above the nocturnal boundary layer over the last 6 hours.

3.1 Sensitivity of daytime dispersion patterns to soil moisture

The primary impact of soil moisture variation is to alter the partitioning of net incoming radiative energy input into sensible (Figure 3a) and latent heat fluxes (Figure 3b) which exhibits a nonlinear response. As the initial soil saturation increases from 20-40%, the amount of net incoming radiation utilised for physical evaporation and transpiration increases approximately in proportion to the variation in soil saturation, while the sensible heat flux decreases. A further increase in soil saturation to 50% causes a disproportionate change in the amount of incoming net radiation that is utilised for physical evaporation and transpiration. Variation in initial soil saturation from 30% in the S2 experiment to 40% in the S3 experiment results in an increase of approximately 100 W m^{-2} in the maximum simulated latent heat fluxes (a decrease of approximately 50 W m^{-2} in sensible heat fluxes), while a further change in soil saturation to 50% causes an increase of more than 300 W m^{-2} in the maximum simulated latent heat fluxes (decrease of $\approx$400 W m^{-2} in the sensible fluxes) in the S4 experiment.

The manner in which the initial soil saturation modulates the partitioning of the incoming net radiation is also reflected in atmospheric dispersion patterns associated with experiments S1-S5 (Figure 4). In general, the areal extent of the dispersion pattern decreases with increasing soil saturation and most significant changes in the dispersion pattern occur when the initial soil saturation is increased from 40% in S3 to 50% in the S4 experiment. In the different experiments, releases were transported over distances ranging from 50-100 km in 12 hours, with comparable dimensions for lateral spreading.

Dispersion patterns found in experiments with higher initial soil saturation (S4 & S5) are reminiscent of Gaussian plume dispersion patterns (Figure 4j-4o), while those observed in experiments with lower initial soil saturation (S1-S3) are distinctly non-Gaussian (Figure 4a-4i). For example the dispersion pattern associated with release R1 exhibits significant curvature in experiments S1-S3 (Figure 4a, 4d, 4g) while it is significantly more linear in experiments S4 and S5 (Figure 4j, 4m). Curvature in the dispersion pattern is related to curvature in the flow field induced by the differences in vegetation type (Figure 1b) in the vicinity of the R1 and R2 release locations. Curvature in the flow field also causes the dispersion pattern associated with the R2 release to wrap around and assume a near circular shape (Figure 4b, 4e, 4h) in experiments S1-S3, while the corresponding dispersion pattern in the S4-S5 experiments is linear (Figure 4k, 4n). A Y-shaped dispersion pattern is found for release R3 in experiments S1-S3 (Figure 4c, 4f, 4i) compared to a linear pattern with a NW orientation that occurs in experiments S4-S5 (Figure 4l, 4o). Topographical channelling is evident in the dispersion pattern for R3 in experiments S1-S3 (Figure 4c, 4f, 4i), where the Y shape of the particle plume confirms a division of atmospheric flow into two pathways around the topographic ridge T1 (Figure 1b). The dispersion pattern for R3 in experiments S4-S5 (Figure 4l, 4o) shows that topographic flow features responsible for the Y-shaped dispersion pattern in experiments S1-S3 did not develop under conditions of higher soil saturation.

Experiments S1-S5 show that both vegetation and topographic heterogeneity effects are modulated by soil moisture with drier conditions enhancing the impact of these heterogeneities. Wetter conditions damp flow features generated by heterogeneities in vegetation and topography.

The response of atmospheric dispersion to soil moisture conditions is nonlinear with dispersion patterns abruptly switching as the soil saturation exceeds 40%.

3.2 Sensitivity of daytime atmospheric dispersion to vegetation and terrain heterogeneity

In order to examine the impact of terrain and vegetation heterogeneities on atmospheric dispersion, patterns of dispersion for releases R1-R3 in S3 (Figure 4g, 4h, 4i), and the TVHOM, THOM, and VHOM experiments (Figure 5) are intercompared. The TVHOM, THOM, and VHOM experiments show that the dispersion patterns are substantially different when topographic, vegetation heterogeneity, or both types of land surface heterogeneities are absent (Figure 5). When both topographic and vegetation heterogeneities are absent, the dispersion patterns are essentially Gaussian with the R1-R3 releases transported in a northwesterly direction in experiment TVHOM (Figure 5a, 5b, 5c). In comparison to the S3 experiment, the transverse spread is highest for the R2 release in the TVHOM experiment (Figure 5b) while it is relatively constrained for releases R1 and R3 (Figure 5a, 5b). In the THOM experiment, where topographic heterogeneity is removed, the dispersion pattern for the R1 release (Figure 5d) exhibits a non-Gaussian structure with the plume branching in multiple directions. The dispersion pattern associated the R2 release in the THOM experiment (Figure 5e) show more closely a Gaussian dispersion behaviour while the R3 release pattern (Figure 5e) is impacted by flow curvature. Removal of vegetation heterogeneity while maintaining topographic heterogeneity in VHOM experiment results in the dispersion pattern for R1 release to be Gaussian (Figure 5g). The R2 and R3 releases in VHOM experiments (Figure 5h, 5i) show some non-Gaussian dispersion features with asymmetrical distortion of the plume geometry and curvature effects as well.

Intercomparison of the TVHOM, THOM, and VHOM experiments show that vegetation heterogeneities cause the maximum deviation from Gaussian dispersion characteristics.

Vegetation heterogeneity also amplifies the impact the topographical heterogeneities and thus the combined effect of both factors on atmospheric dispersion is significant. This is also evident in the near-surface divergence field that show land surface heterogeneities force mesoscale flow features with dimensions comparable to the plumes (Figure 6). The action of these mesoscale circulation features on plume dispersion result in non-Gaussian characteristics. Note that the surface divergence field is very similar for the THOM and S3 (Figure 6b and 6d) experiment and it is very different compared to the TVHOM and VHOM (Figure 6a and 6c) experiments. This indicates that the variability in the divergence field is primarily influenced by vegetation heterogeneity. Comparison of the near-surface divergence field from the VHOM and S3 experiments (Figure 6c and 6d) show that terrain-induced divergence features (for example features D1 and D2 in Figure 6c) are amplified by the addition of vegetation heterogeneity.

3.3 Sensitivity of nocturnal atmospheric dispersion to vegetation and terrain heterogeneity

Comparison of releases R1-R3 in the TVHOM, THOM, VHOM, and S3 experiments (Figure 7) show that nocturnal atmospheric dispersion is very sensitive to terrain and vegetation heterogeneities. When both topographical and vegetation heterogeneities are removed, the nocturnal dispersion patterns for releases R1-R3 (Figure 7a, 7b, 7c) are essentially Gaussian in nature with substantial spreading in the direction transverse to the axis of transport.

In the THOM experiment, where vegetation heterogeneity is considered independent of topographic heterogeneity, the nocturnal dispersion patterns deviate significantly from Gaussian dispersion (Figure 7d, 7e, 7f). For release R1, part of the plume wraps around and propagates eastward while the other part of the plume is propagated northward (Figure 7d). The plume in the R2 release propagates northward with the plume extent in the east-west direction decreasing in the northward direction. Parts of the R3 release plume propagate in a southerly direction while other parts propagate northward.

The releases R1-R3 in the VHOM experiment show that terrain heterogeneity also has a significant impact on nocturnal dispersion patterns. The R1 release (Figure 7g), located in a region with relatively small terrain variations, shows behaviour similar to that observed in the TVHOM experiment (Figure 7a). However, the impact of terrain heterogeneity on dispersion patterns for the R2 and R3 releases is to make them significantly non-Gaussian (Figure 7h and 7i). The R2 release plume initially propagates northwest and then curves in an easterly direction while the leading edge of the R3 plume is asymmetrically elongated in the easterly direction.

The combined impact of both terrain and vegetation heterogeneity on nocturnal dispersion is to make it substantially non-Gaussian in nature (Figure 7j, 7k, 7l). The plume associated with release R1 experiences significant curvature (Figure 7j) and elongation. The R2 release plume also shows effects of flow curvature (Figure 7k) while the leading edge of the R3 release plume assumes a crescent shape (Figure 7l).

The influence of surface heterogeneity on the air flow can also be found in the nighttime vertical profile of the horizontal wind (Figure 8). Comparison of the TVHOM experiment to the others shows that the influence is most prominent in the lower troposphere as the effect is most immediate at those levels and the influence extends over the daytime CBL within 2-3 km in the vertical. The THOM experiment shows that the vegetation heterogeneity can have a significant impact as demonstrated by the wind shift to southwesterly with speeds of more than 10 m s^{-1} to southeasterly at less than 5 m s^{-1} in the TVHOM run between longitudes 88°W and 87°W. Compared to the TVHOM experiment, the presence of topography and topographical heterogeneity in the VHOM and S3 experiments exerts a strong influence in the layer extending to more than 4 km vertically as shown by the drastic departure of the wind aloft from that in the lower layer. Furthermore, the strong wind shear in both the vertical and horizontal can spread the particles wide across the area in the nighttime regime, especially in the case inherited an already widespread plume from the daytime dispersion as shown in Figure 7i (VHOM) and 7l (S3).

3.4 Sensitivity of daytime and nocturnal atmospheric dispersion to soil moisture heterogeneity and use of satellite-derived vegetation characteristics

Sensitivity of atmospheric dispersion to soil moisture heterogeneity is explored by comparing dispersion patterns for releases R1-R3 in the HET1 and S4 experiments. The S4 experiment was selected for comparison purposes since the 50% soil saturation value used in the S4 experiment is representative of average soil moisture conditions used in the HET1 and HET2 experiments. The daytime dispersion patterns for releases R1-R3 are very similar in both the S4 (Figure 9a, 9b, 9c) and HET1 experiments (Figure 9d, 9e, 9f). The reason for this lack of sensitivity is the high soil saturation values found in the domain and as noted in section 4.1, wetter soil conditions tend to suppress heterogeneity effects. Dispersion patterns for releases R1-R3 did not substantially deviate from Gaussian dispersion patterns in both the S4 and HET1 experiments. Primary differences found between dispersion patterns in the S4 and HET1 experiments are the extent of lateral spread, plume orientation, and curvature. Dispersion patterns for the R1 and R2 releases in S4 experiment (9b, 9c) exhibited more lateral spread compared to their counterparts in the HET1 experiment (9e, 9f). The plume geometry for R1 release in HET1 is more symmetric along the major axis as compared to that found in the S4 experiment.

The sensitivity of dispersion patterns to the use of satellite-derived vegetation characteristics is also small due to the wet soil conditions. The daytime comparison of R1-R3 releases in the HET1 (Figure 9d, 9e, 9f) and HET2 (Figure 9g, 9h, 9i) experiments show that the primary difference in dispersion patterns is the lateral plume spread. The most substantial difference in lateral plume spread is found for the R1 release. The plume for the R1 release is substantially thinner in the HET2 experiment (Figure 9g) than its counterpart in the HET1 simulation (Figure 9d).

Imposition of soil type heterogeneity has a dramatic impact on the daytime dispersion patterns for all releases. The R1 release initially proceeds in a northwesterly direction and then shifts towards the northeast in both the HET3 and HET4 experiment (Figure 9j, 9m). The section of the R1 plume oriented in the northeast direction in the HET3 experiment (Figure 9k) shows a transverse spread while this feature is absent in the HET4 experiment (Figure 9n). The R2 release displays a complex pattern with multiple branches oriented in the northeast, west, and west-southwest directions in the HET3 experiment (Figure 9k). The R2 release patterns exhibit less areal extent in the HET4 experiment, with the northeast branch shifting toward the east-northeast and both the other branches exhibiting a southerly shift (Figure 9n). The R3 release pattern also presents with a significant difference than the HET3 experiment (Figure 9l), where it is initially oriented west-northwest and later in a northeast direction extending further north in comparison to a corresponding feature in the HET1 experiment. The R3 release feature oriented in a northeasterly direction in the HET3 experiment is shifted towards the east-northeast direction in the HET4 experiment (Figure 9o) and does not travel as far north as its counterpart in the HET3 experiment. The transverse spread of this feature is less in HET4 compared to the HET3 experiment.

Nocturnal dispersion patterns are significantly impacted by both soil moisture heterogeneity and the satellite-derived vegetation spatial distribution of vegetation characteristics

(Figure 10). The lateral spread of the plumes during nighttime is more substantial under homogeneous soil moisture conditions (S4 experiment; Figure 10a, 10b, 10c) compared to a heterogeneous distribution of soil moisture (HET1, HET2 experiments; Figure 10d-10f and 10g-10i). Soil moisture heterogeneity also impacts the plume propagation distance, orientation, and geometry. The R1 release plume crosses the Alabama-Mississippi border in the HET1 experiment (Figure 10a) but it does not approach the border in the S4 experiment (Figure 10d). The plume area for the R2 and R3 releases is significantly smaller in the HET1 experiment (Figure 10e, 10f) compared to S4 experiment (Figure 10b, 10c).

For a heterogeneous soil moisture distribution, the use of satellite-derived vegetation characteristics further alters nocturnal dispersion patterns for releases R1-R3 (Figure 10g-10i). Plumes for all three releases propagate less distance when satellite-derived vegetation characteristics are utilised. While the R1 release plume reaches the vicinity of the Alabama-Mississippi border in the HET2 experiment (Figure 10d), it does not cross the state border into Mississippi as in the HET1 experiment (Figure 10g). The R2 release plume extends more in the north and south directions in the HET1 experiment (Figure 10e) compared to that in the HET2 experiment (Figure 10h), while the R3 release plume extends more to the north in the HET1 experiment (Figure 10f) than its counterpart in the HET2 experiment (Figure 10i).

The addition of soil type heterogeneity introduces the most dramatic changes to the nocturnal dispersion patterns of releases R1-R3. Introduction of heterogeneous soil type causes the areal extent, geometry and orientation of the release plume to alter dramatically (Figure 10j-10o). The shape of the dispersion patterns in both the HET3 and HET4 experiments are substantially more irregular when compared to those in the S4, HET1, and HET2 experiments. The areal extents of all the release plumes are also much higher in the HET3 and HET4 experiments compared to their counterparts in other experiments. Comparison between the HET3 and HET4 experiment show that the main impact of using satellite data to constrain the model simulations is to reduce the areal extent of the plume dispersion patterns. There are also some changes to the shape of the dispersion patterns with enhanced northern spread of the R1 release plume (Figure 10j) and a westerly spread of portions of the R2 and R3 release plumes (Figure 10k, 10l) being more prevalent in the HET3 experiment compared to HET4 (Figure 10m, 10n, 10o).

The mid-day near-surface divergence field shows that inclusion of soil type heterogeneity enhances the generation of mesoscale circulation features (Figure 11). Differences in the divergence field between the HET1 and HET2 experiments are minimal (Figure 11a, 11b). The near-surface divergence field for the HET3 experiment shows the existence of several local maxima of convergence (Figure 11c). The use of satellite data to constrain vegetation characteristics leads to some of these convergence maxima being less intense, but still there are more active regions of convergence than are present in the HET1 and HET2 experiments. The enhancement of mesoscale circulations in the study area is reflected in the dispersion patterns for the HET3 and HET4 experiments which exhibit more areal spread and shape distortion compared to HET1 and HET2 experiments.

4 Discussion

While prior studies have examined the impact of surface heterogeneities on atmospheric dispersion at multiple spatial scales (Gopalakrishnan and Avissar 2000; Gopalakrishnan et al. 2000; Pielke and Uliasz 1993), the sensitivity of mesoscale atmospheric dispersion to land surface heterogeneity is still not well understood. Such knowledge is essential for improving predictions for regional and long-range transport, especially through the utilisation of data assimilation techniques.

Atmospheric models, such as RAMS, use SVAT models (LEAF-2) to parameterise land-atmospheric interactions. However the performance of SVAT models is dependent on the proper specification of vegetation characteristics such as roughness, leaf area index, vegetation fraction, albedo, soil moisture, etc. While it is possible to determine the important vegetation characteristics at adequate spatial resolutions using satellite remote sensing, soil moisture measurement at the needed spatial and temporal resolution are scarce. However, techniques that constrain surface energy flux and moisture partitioning in the SVAT using either satellite observations of skin surface temperature (Jones et al. 1998a, 1998b; McNider et al. 1994, 2005) or remotely-sensed surface soil moisture estimates (Reichle et al. 2002, 2007, 2008), or *in-situ* soil moisture measurements (De Lannoy et al. 2007), surface meteorological observations (Alapaty et al. 2008), or other satellite data (Matsui et al. 2007, 2008) can be used indirectly to account for spatial heterogeneity of soil moisture.

Numerical model experiments conducted in this study show that atmospheric dispersion in both the convective and nocturnal boundary layer are sensitive to the nature of land surface heterogeneity. The MODIS land product dataset is effective for realistic specification of vegetation heterogeneity in mesoscale atmospheric models.

However, sensitivity experiments S1-S5 show that soil moisture plays an important role in modulating the impact of terrain and vegetation heterogeneity on atmospheric dispersion. Thus realistic specification of vegetation heterogeneity alone is not sufficient but needs to be coupled with a realistic distribution of soil moisture. Data assimilation techniques that utilise satellite skin temperature (McNider et al. 2005), surface meteorological observations (Alapaty et al. 2008), or an integrated land surface assimilation analysis (Matsui et al. 2007) are capable of indirectly accounting for soil moisture heterogeneity. Since the data assimilation techniques are aimed at constraining the SVAT model to generate realistic spatial distribution of sensible and latent heat fluxes, it may appear that it is unnecessary to introduce satellite-derived spatial distribution of vegetation characteristics when such techniques are being utilised. However, substantial differences in nocturnal atmospheric dispersion patterns between the HET1 and HET2, HET3 and HET4 experiments (Figure 10d-10f and 10g-10i) show that it is also necessary to realistically specify vegetation heterogeneity. The realistic spatial distribution of surface sensible heat flux is important for dispersion in the convective boundary layer while the spatial variation in vegetation characteristics such as roughness and fractional vegetation cover is important for dispersion in the nocturnal boundary layer where the impact of mechanically-generated turbulence dominate. The spatial variation in vegetation roughness may be also important for daytime dispersion since it could result in acceleration or deceleration of near-surface flow and induce regions of convergence/divergence.

The dramatically different dispersion patterns found in HET3 and HET4 also show that soil-type heterogeneity plays an important role in determining the dispersion pattern.

Experiments conducted in this study show that satellite-derived vegetation characteristics, soil type data, and data assimilation techniques all have the potential to improve the predictability of atmospheric dispersion.

5 Conclusions

This study examines the relative role of topography, vegetation, and soil moisture heterogeneity on mesoscale atmospheric dispersion using a Lagrangian particle dispersion model coupled with RAMS, an Eulerian meteorological model. Prior studies have focused on atmospheric dispersion in the convective boundary layer at smaller spatial scales forced by idealised patterns of spatial heterogeneity. This study utilises realistic topographic, vegetation, and soil moisture heterogeneities in numerical experiments designed to isolate the impact of each of these heterogeneities. Numerical experiments show a strong dependency of atmospheric dispersion on all the factors discussed above. Specific findings from this study include:

1. Numerical model experiments show that the impact of vegetation and terrain heterogeneities are modulated by soil moisture. Dispersion patterns show a nonlinear response to soil moisture with the patterns switching from non-Gaussian to near-Gaussian behaviour when soil saturation exceeds 40%.
2. Sensitivity experiments show that soil type and vegetation heterogeneities cause a maximum deviation from Gaussian dispersion behaviour. Deviation from Gaussian dispersion behaviour is primarily due to the action of mesoscale circulation features induced by heterogeneous soils, vegetation, and terrain.
3. The primary forcing for mesoscale circulation features is differential heating related to soil and vegetation heterogeneity.
4. The nocturnal dispersion is very sensitive to heterogeneity in topography, vegetation, soil moisture, and soil type.
5. Numerical simulation of atmospheric dispersion is also sensitive to the use of satellite-derived vegetation characteristics and especially impacts nighttime dispersion.

The numerical experiments in our study suggest that the utilisation of satellite data to specify vegetation heterogeneity coupled with the use of assimilation techniques that constrain SVAT models to generate realistic spatial distribution of surface energy fluxes have the potential to improve the prediction of atmospheric dispersion. The sensitivity of atmospheric dispersion to the use of the assimilation techniques of Alapaty et al. (2008), Matsui et al. (2007), and McNider et al. (2005), and, therefore, need to be considered in future studies. Improvements in the performance of the dispersion modelling system utilising satellite vegetation data and data assimilation techniques also needs to be quantified by comparing against observations.

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Figure Captions

Fig. 1 (a) The two nested grid domains of the simulation are drawn in bold lines and the release sources are indicated by the triangle symbols ; (b)-(e) surface characteristics used for the grid 2 simulation domain: (b) topography from the RAMS dataset; (c) RAMS vegetation classes; (d) soil texture classes; (e) top most layer soil moisture from NAM data. Also, in (b)-(e) the dash-lined box indicates the plotting domain used in the dispersion plots in **Figs 4**, **5**, **7**, **9 and 10**, and the three little triangles, R1, R2 and R3 mark the release sources locations.

Fig 2 Vegetation information used in the simulations. (a) LAI from RAMS; (b) LAI from MODIS; (c) vegetation fraction from RAMS; (d) vegetation fraction from MODIS; (e) albedo of vegetation from RAMS; (f) albedo of vegetation from MODIS. The MODIS data are in May 2007.

Fig. 3 For the soil moisture sensitivity runs averaged over the grid 2 domain for: (a) surface sensible heat flux, and (b) surface latent heat flux.

Fig. 4 The 12 hour (12-24 UTC, May 21, 2007), daytime dispersion patterns for R1-R3 releases for S1, S2, S3, S4, and S5 experiments are shown in panels a-c, d-f, g-i, j-l, and m-o respectively. The bold black line indicates the Alabama state borders. The states of Mississippi, Tennessee, and Georgia are to west, north, and east of Alabama, respectively.

Fig. 5 The 12 hour (12-24 UTC, May 21, 2007), daytime dispersion patterns for R1-R3 releases for TVHOM, THOM, VHOM, and S3 experiments are shown in panels a-c, d-f, g-I, and j-l respectively. The bold black line indicates the Alabama state borders. The states of

Mississippi, Tennessee, and Georgia are to west, north, and east of Alabama, respectively.

Fig. 6 Near-surface divergence field at 18 UTC for a) TVHOM,; b) THOM; c) VHOM; and d) S3 experiments. Note the sign has been reversed so that positive and negative values indicate convergence (upward motion) and divergence (downward motion) respectively.

Fig. 7 Six hour nocturnal dispersion patterns (00-06 UTC, May 22, 2007) for R1-R3 releases for TVHOM, THOM, VHOM, and S3 experiments are shown in panels a-c, d-f, g-I, and j-l respectively. The bold black line indicates the Alabama state borders. The states of Mississippi, Tennessee, and Georgia are to west, north, and east of Alabama, respectively. The dashed line indicates the location where cross sectional wind profile is plotted in Fig. 8.

Fig. 8 Model-simulated wind profile at 06 UTC, May 22, 2007, along a cross section indicated by the dashed line on Fig 7 for: (a) TVHOM case run; (b) THOM; (c) VHOM; and (d) S3. The topographical profile is indicated by the black line near the bottom of panel c and d. The wind speed is indicated both by colour and length of the barb and the orientation of the barb is the direction from which the wind blows.

Fig. 9 The 12 hour (12-24 UTC, May 21, 2007), daytime dispersion patterns for R1-R3 releases for S4, HET1, HET2, HET3, and HET4 experiments are shown in panels a-c, d-f, g-i, j-l, and m-o respectively. The bold black line indicates the Alabama state borders. The states of Mississippi, Tennessee, and Georgia are to west, north, and east of Alabama, respectively.

Fig. 10 Six hour nocturnal dispersion patterns (00-06 UTC, May 22, 2007) for R1-R3 releases for S4, HET1, HET2, HET3, and HET4 experiments are shown in panels a-c, d-f, g-i, j-l, and m-o respectively. The bold black line indicates the Alabama state borders. The states of Mississippi, Tennessee, and Georgia are to west, north, and east of Alabama, respectively..

Fig. 11 Near-surface divergence field of at 18 UTC, May 21, 2007 for a) HET1; b) HET2; c) HET3; and d) HET4 experiments. Note the sign has been reversed so that positive and negative values indicate convergence (upward motion) and divergence (downward motion) respectively.

Table 1 Description of the numerical experiments utilised in this study

Experiment Name	Description
S1-S5	Atmosphere initialised using NAM 0600 UTC analysis fields for 5/21/2007. Uniform soil saturation (horizontal and vertical) of 20%, 30%, 40%, 50%, and 60% assumed for experiments S1-S5 respectively. Soil type is also assumed to be same for the entire domain (sandy clay loam).
THOM	Same as S3, except for the assumption of flat terrain.
VHOM	Same as S3, except for the assumption of homogenous vegetation cover of evergreen needle leaf tree.
TVHOM	Same as VHOM, except for the additional assumption of flat terrain.
HET1	Heterogeneous terrain, soil type, land use and soil moisture distribution. Vegetation characteristics are RAMS-specified values that are function of vegetation type.
HET2	Same as HET1, except for the use of satellite-derived vegetation characteristics.
HET3	Same as HET1, except for the use of heterogeneous distribution of soil type.
HET4	Same as HET3, except for the use of satellite-derived vegetation characteristics.

colour figure

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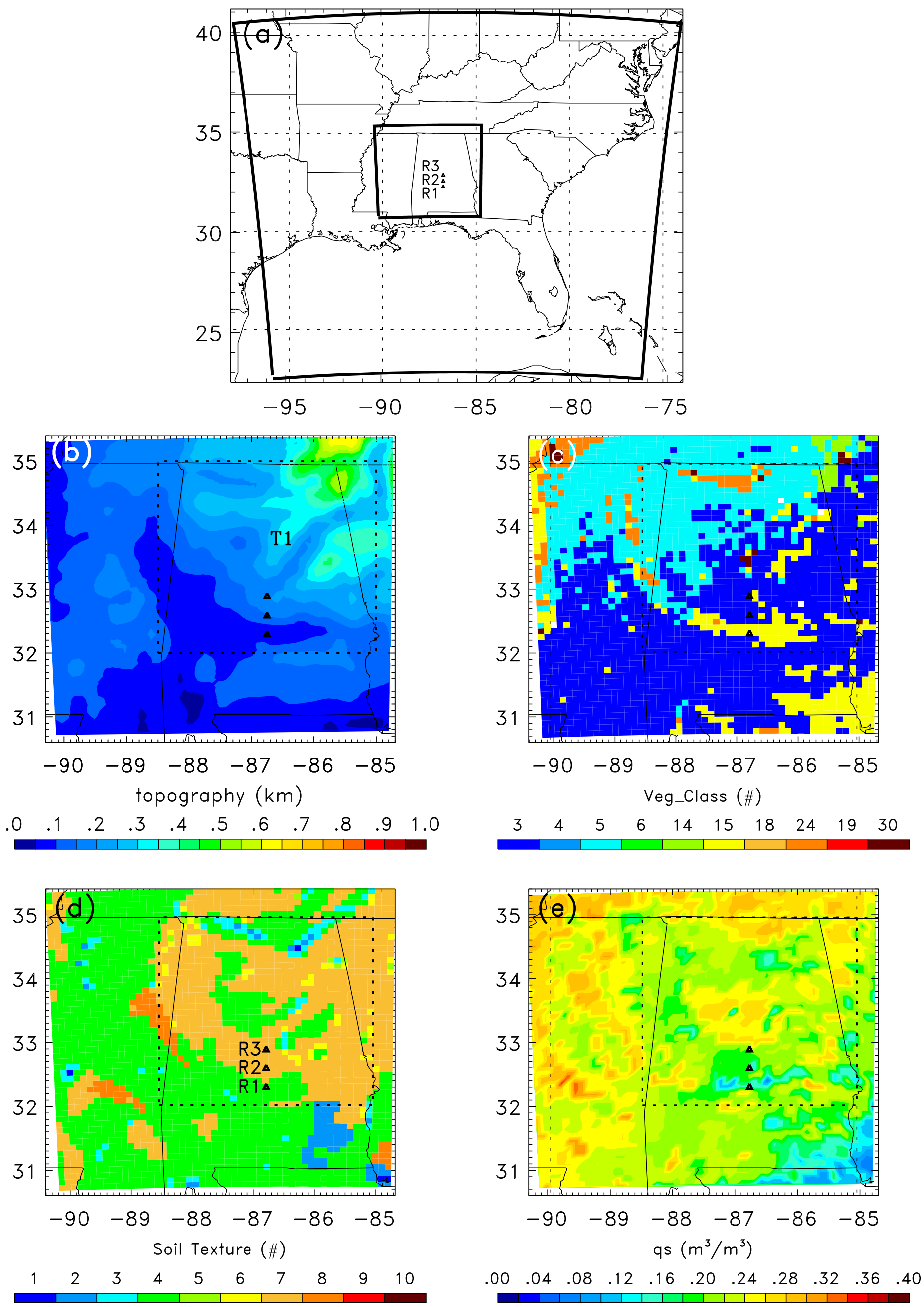

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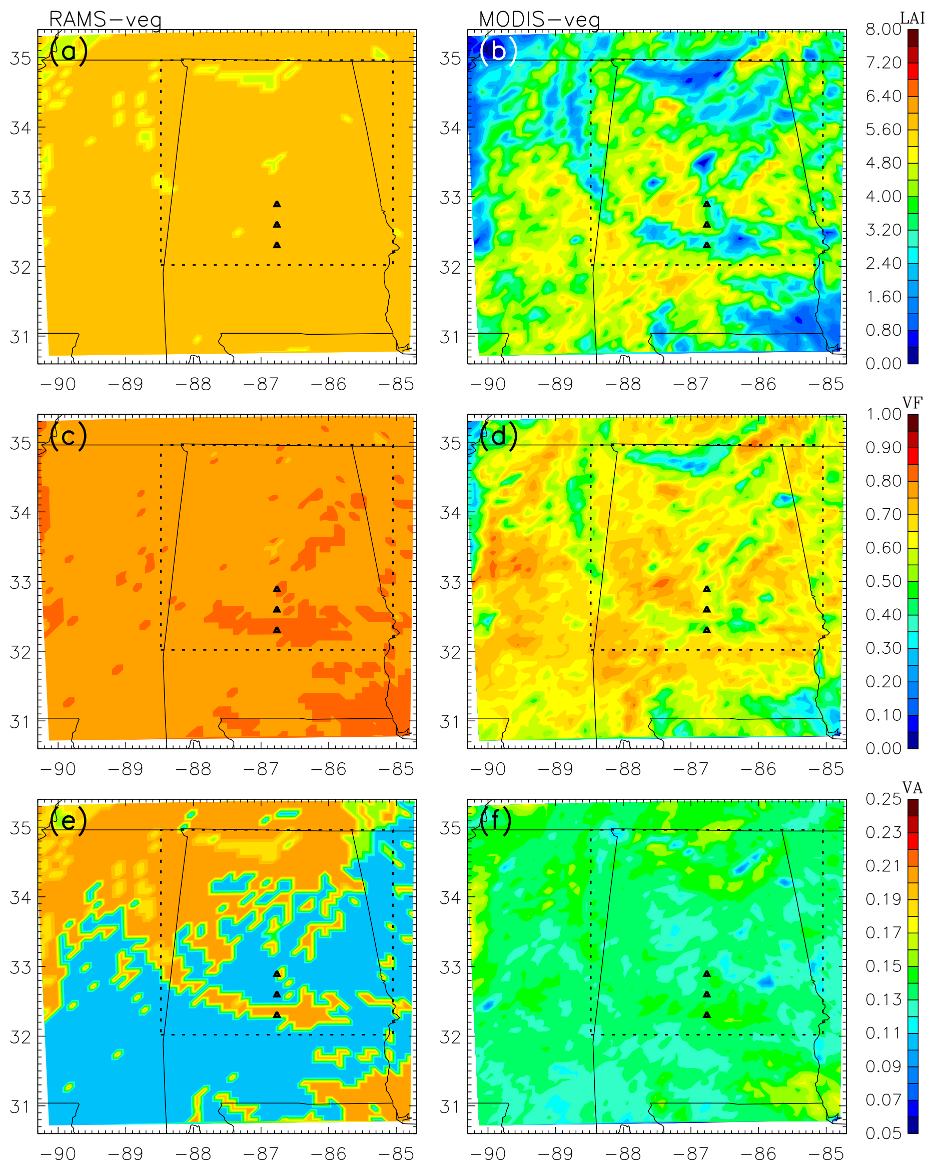

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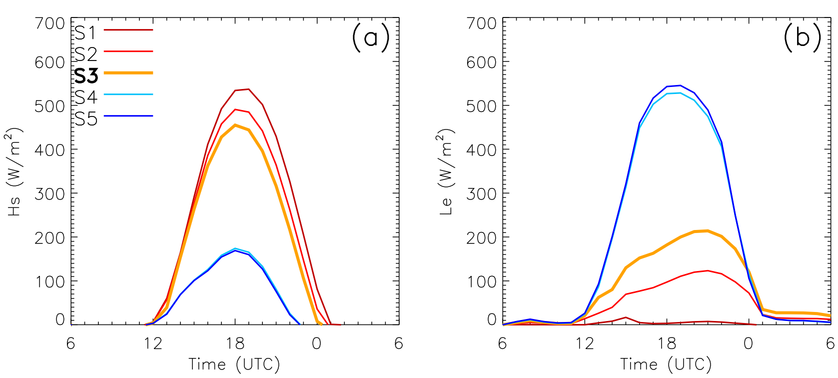

line figure

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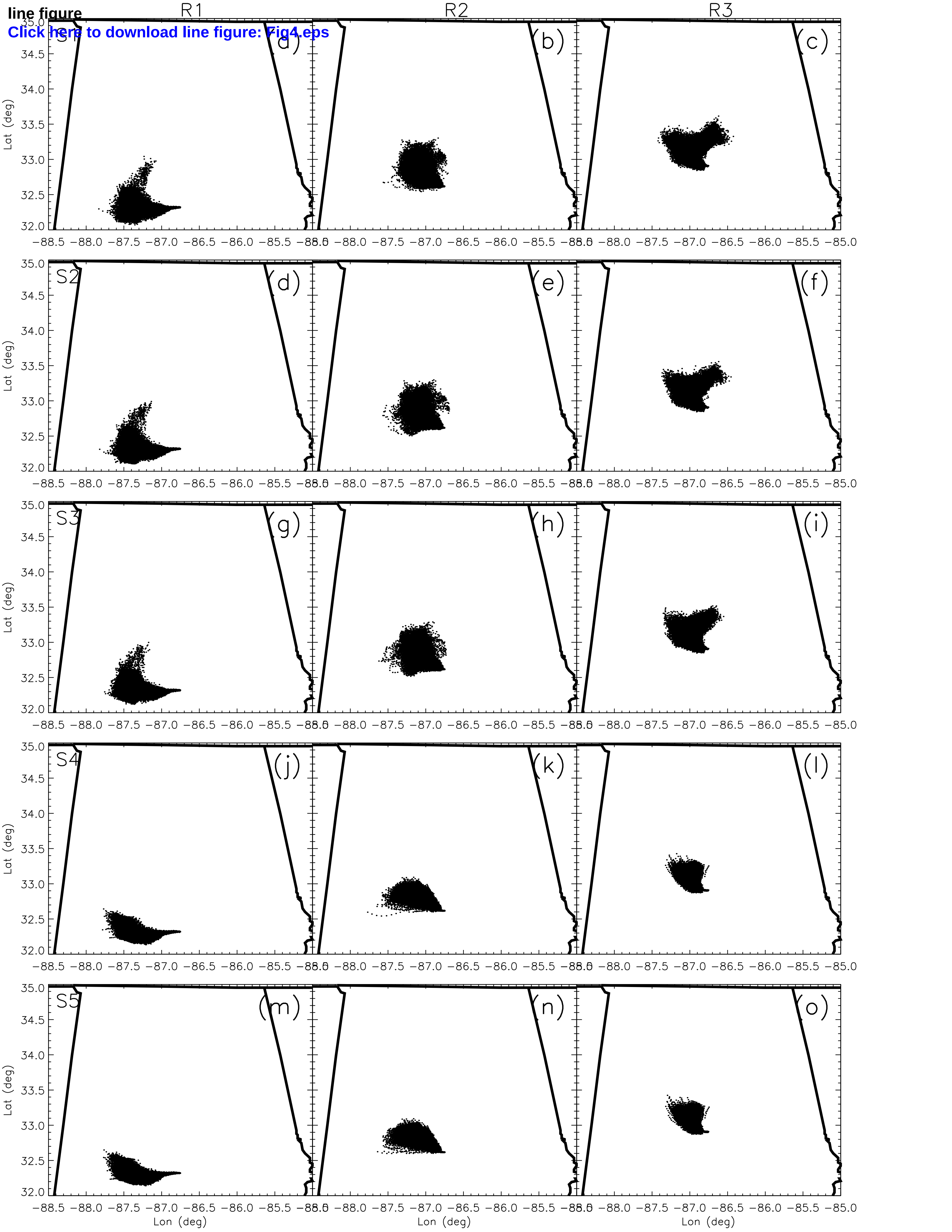

line figure

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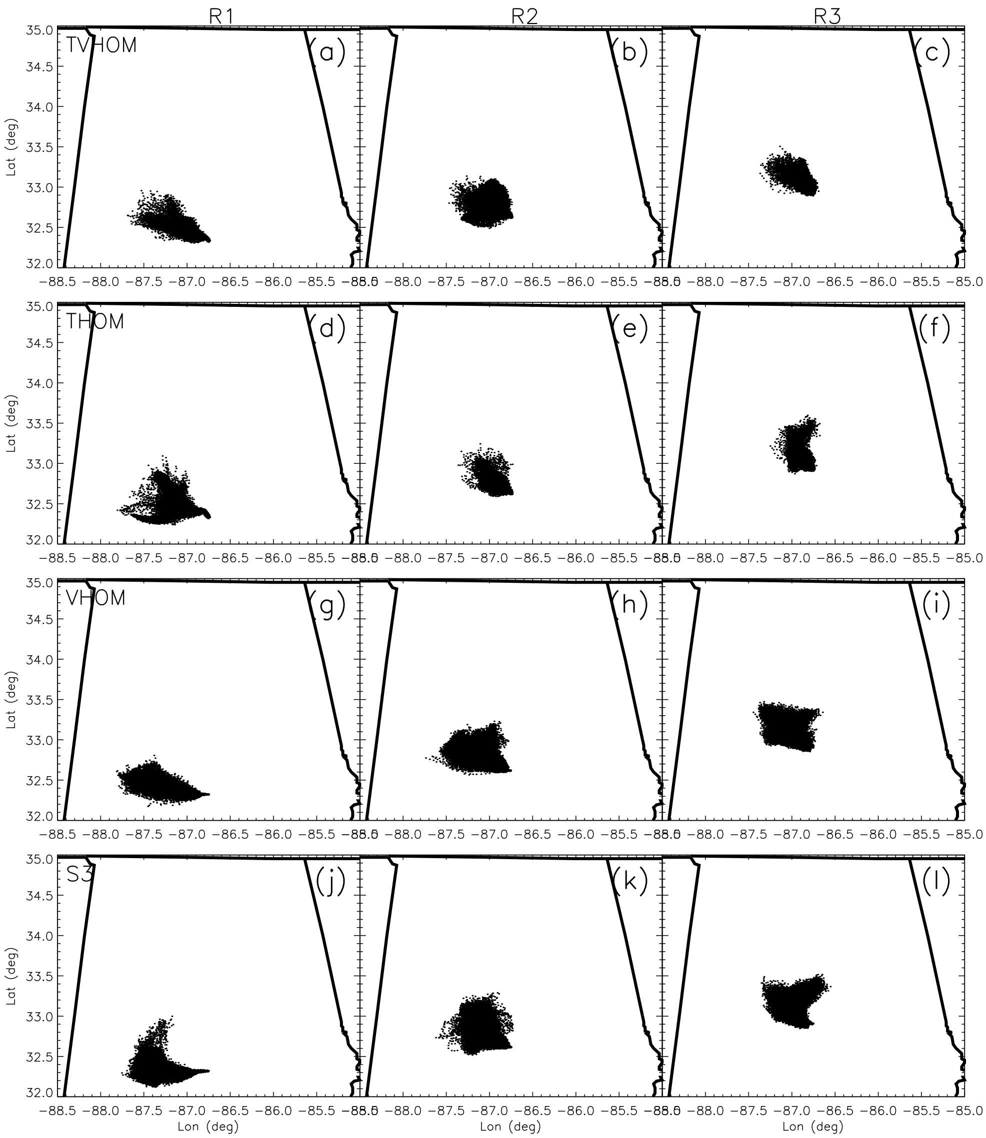

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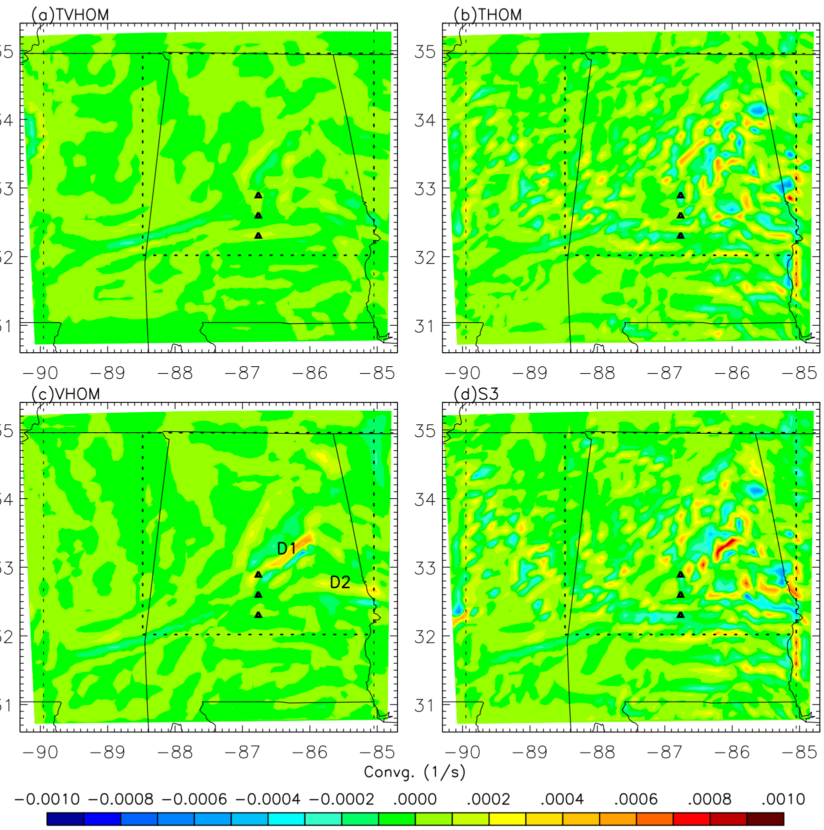

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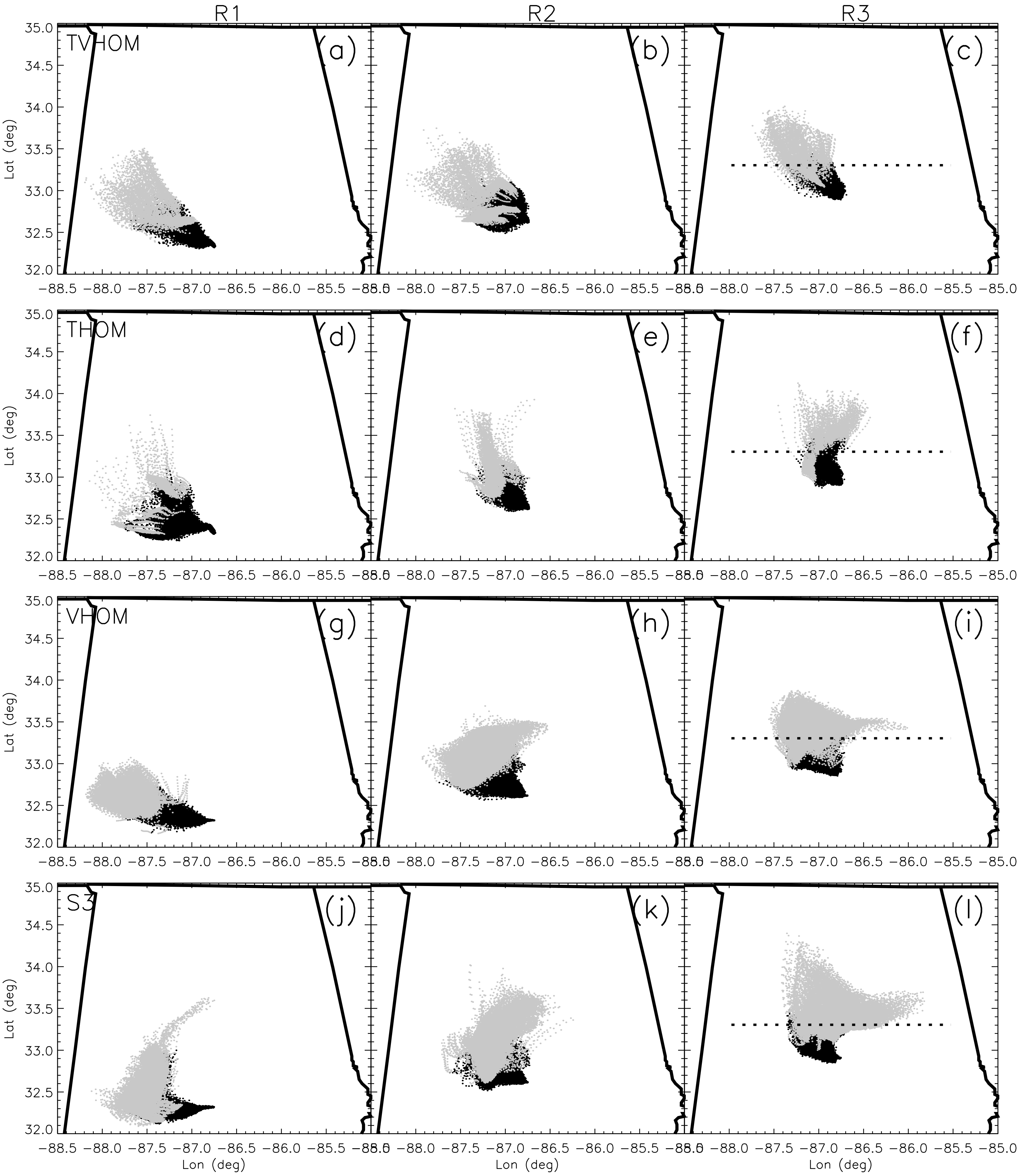

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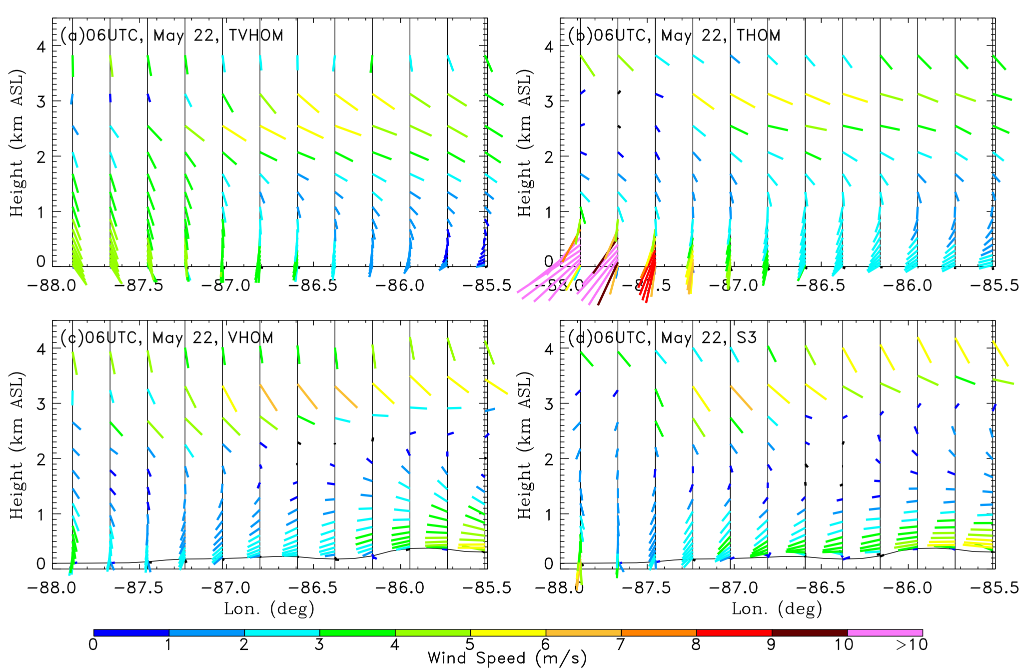

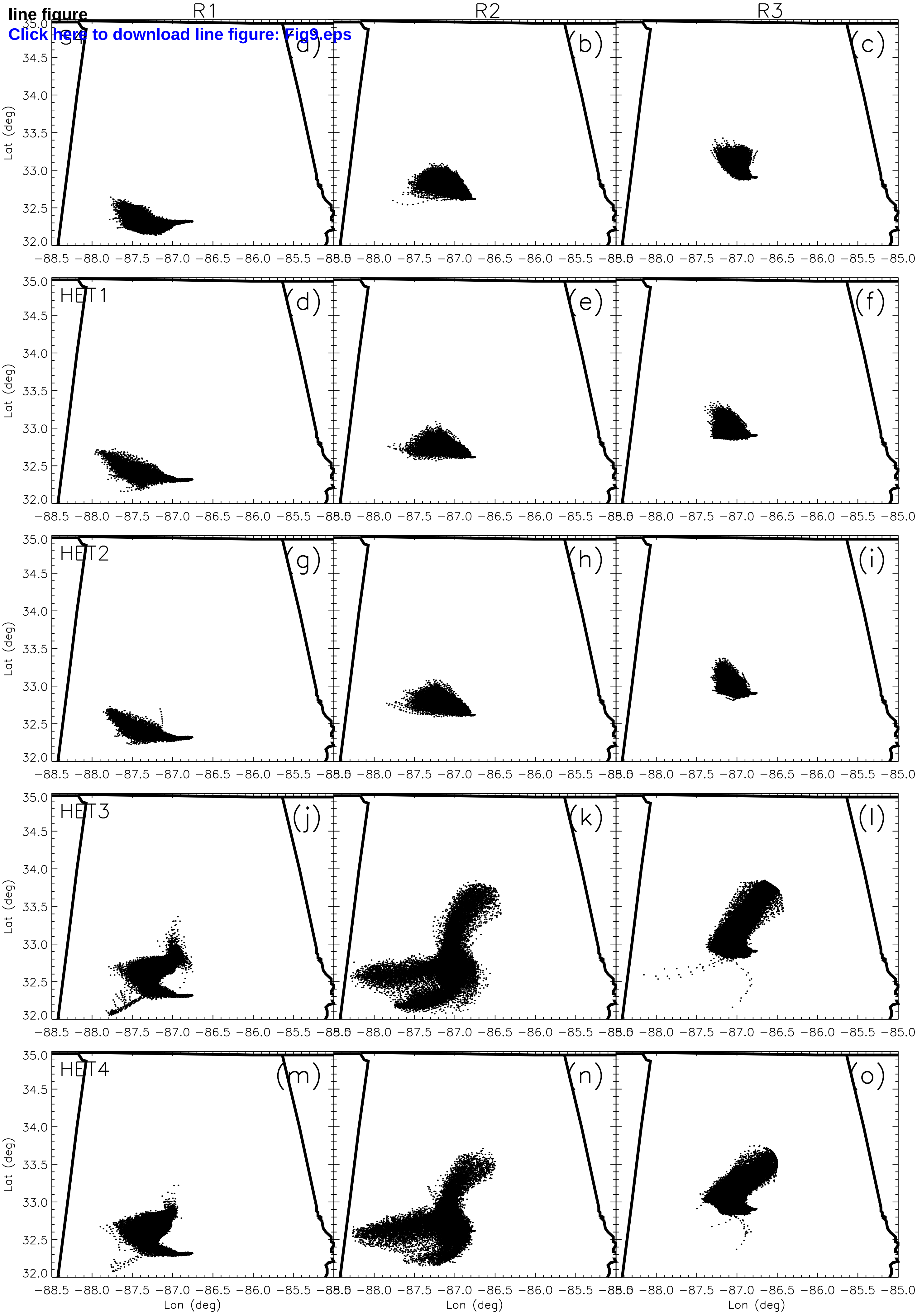
R1
R2
R3
(a)
(b)
(c)
HET1
(d)
(e)
(f)
HET2
(g)
(h)
(i)
HET3
(j)
(k)
(l)
HET4
(m)
(n)
(o)
Lat (deg)
Lon (deg)
35.0 34.5 34.0 33.5 33.0 32.5 32.0
−88.5 −88.0 −87.5 −87.0 −86.5 −86.0 −85.5 −85.0

line figure

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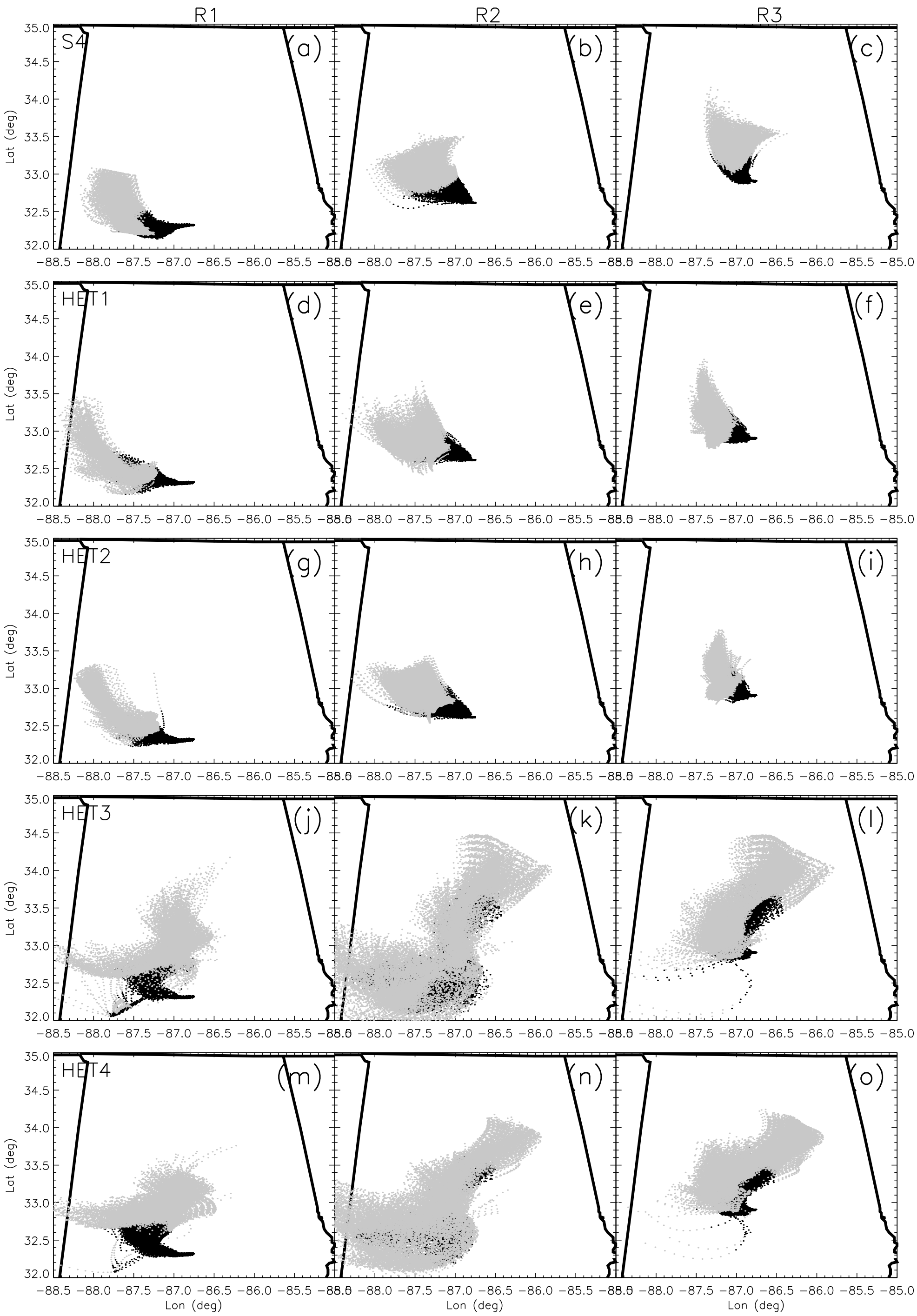

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