

**REGIONAL ANALYSIS AND SPATIOTEMPORAL
BEHAVIOR OF SOIL MOISTURE IN PARTITIONING THE
HEAT FLUXES: A THEORY BASED ON MODEL**

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BEHAVIOR OF SOIL MOISTURE IN PARTITIONING THE
HEAT FLUXES: A THEORY BASED ON MODEL**

by

Aniket Chakravorty

Department of Civil Engineering

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



Indian Institute of Technology Delhi

APRIL 2018

DEDICATED TO

My Family

&

My Teachers

Certificate

This is to certify that the dissertation entitled “**REGIONAL ANALYSIS AND SPATIOTEMPORAL BEHAVIOR OF SOIL MOISTURE IN PARTITIONING THE HEAT FLUXES: A THEORY BASED ON MODEL**” which is being submitted by **Mr. Aniket Chakravorty**, for the award of the degree of **Doctor of Philosophy** in Civil Engineering, to the Indian Institute of Technology Delhi is a record of bonafide work carried out by him under our sustained guidance and supervision. The dissertation has reached the standard fulfilling the requirements of the regulations relating to the degree. The results embodied in the dissertation have not been submitted to any other university or institute for the award of any degree or diploma.

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Abstract

The interaction between land and atmosphere is complex and non-linear in nature. The mode of this interaction between land and atmosphere is governed by fluxes. It depends on many controlling factors that are both dynamic and static in nature. The work carried out in this thesis tried to investigate the spatiotemporal behavior of soil moisture and turbulent heat fluxes, viz., latent and sensible heat fluxes, under the influence of these controlling factors and understand the role of soil moisture in the proportionate partitioning of the turbulent heat fluxes. To that end a land surface modeling infrastructure, viz., CESM-CLM version-4.5 (CLM4.5) in standalone mode, was used. Such an analysis required the modeling system to produce valid spatiotemporal behavior of land surface states. But the evaluation of a coarse resolution model simulation with finer resolution observation has its own set of challenges. This prompted the introduction of a new set of evaluation metrics that are based on temporal dynamics of the system. A satellite based soil moisture product was used as the observation system because of a paucity of *in-situ* measurements over India. Since, satellites are also known to have its own error characteristics, prior to the model evaluation, an evaluation of the satellite soil moisture products was also undertaken. Based on this, the thesis was divided into three broad objectives: 1. Evaluation of satellite observation systems, 2. Evaluation of the modeling infrastructure, and 3. Spatiotemporal evolution of land surface states. These three objectives form the three main chapters of this work, which are discussed in brief below.

Chapter 2 discusses the evaluation of available satellite soil moisture products over India for an overlapping time period from 2010 to 2013. Four available satellite products were evaluated with a soil moisture reanalysis product from Modern Era Retrospective-analysis for Research and Applications-Land (MERRA-L). Under the aegis of the European

Space Agency-Climate Change Initiative (ESA-CCI) program, three multi-decadal soil moisture datasets were generated by merging all available satellite soil moisture products, viz., all-active-merged product: CCI-A; all-passive-merged product: CCI-P; and all-active-passive-merged product: CCI-C. They were compared with ESA's Soil Moisture Ocean Salinity (SMOS) product. A two-stage evaluation strategy was employed here. First a preliminary time series and correlation analysis was carried out followed by a novel error estimation methodology called Triple Collocation. It was observed that over India the ascending swath of SMOS had higher error than the descending, which prompted the use of the descending swath for further analysis. From both the preliminary time series and correlation analysis and triple collocation analysis, it was observed that active satellites have a higher performance over India except for the western arid and semi-arid regions. This was followed by the CCI-C and then by CCI-P. SMOS showed comparatively high values of error than the rest of the products. However, as SMOS is an L-band sensor compared to ESA-CCI products that are retrieved from C-band sensors, it showed better performance over the dense vegetated regions of India. Based on this analysis, the ESA-CCI products were used for evaluating the modeled soil moisture over India.

Chapter 3 discusses the methodology and the subsequent results of the performance evaluation of CLM4.5 simulated soil moisture. Since, CLM4.5 is being run in a standalone mode with prescribed atmospheric forcings the impact of reanalysis precipitation on the model simulation was also investigated. Two reanalysis rainfall products were used, viz., CRU-NCEP and MERRA2. This inter-comparison analysis showed that the performance of CLM4.5 forced with MERRA2 was better than when it was forced with CRU-NCEP. Thus, the soil moisture simulation of CLM4.5 when forced with MERRA2 rainfall was used for the final performance evaluation of the modeled soil moisture. The performance evaluation methodology employed consists of temporal stability, auto-correlation function, and triple

collocation analysis. Temporal stability and auto-correlation function analysis was used to check the congruency of spatiotemporal dynamics of soil moisture as observed by the model with respect to satellite and reanalysis. This analysis suggested that CLM4.5 is able to capture the spatial and temporal dynamics of observed soil moisture. However it showed high values of random error as estimated from triple collocation.

Chapter 4 demonstrates the behavior of spatiotemporal evolution of soil moisture and the turbulent heat fluxes over India. This is achieved by decomposing them into time-invariant, space-invariant time-variant and space-variant time-variant components. These relate to the control of dynamic and static factors on the behavior of land surface states. Thus, the three decomposed components are able to give the contribution of each controlling factor on the spatiotemporal variability of land surface states. It was observed that over India at a coarser resolution of $0.9^{\circ} \times 1.25^{\circ}$, latent heat flux has a stronger response to soil moisture variability than sensible heat. It was also observed that both latent heat flux and soil moisture are dominated by static controls like soil type, topography, etc. However, sensible heat is dominated by the dynamic controls, like atmospheric condition, land surface temperature, etc. One of the intensions of this work was also to check the viability of a multi-variate land data assimilation system. And based on the results, it can be concluded that for a spatiotemporally variable region like India, a multi-variate data assimilation system is the right way forward. This thesis ends with a few suggestions as to the direction in which the work done in this thesis can be taken.

सामान्य सारांश

भूमि और वातावरण के बीच बातचीत जटिल और गैर-रैखिक प्रकृति में है। भूमि और वायुमंडल के बीच इस बातचीत का तरीका प्रवाह द्वारा शासित है। यह कई नियंत्रण कारकों पर निर्भर करता है जो प्रकृति में गतिशील और स्थैतिक दोनों हैं। इस थीसिस में किए गए काम ने मिट्टी की नमी और अशांत गर्मी प्रवाहकत्वा, अर्थात्, सुगम और समझदार गर्मी प्रवाहकताओं के आकाशीय व्यवहार की जांच करने की कोशिश की, इन नियंत्रक कारकों के प्रभाव में और मिट्टी की नमी की भूमिका को समझने के लिए आनुपातिक विभाजन अशांत गर्मी प्रवाहकत्व इसके लिए एक भूमि सतह मॉडलिंग बुनियादी ढांचे, जैसे सीईएसएम- सीएलएम वी एरियन-4.5 (सीएलएम 4.5) स्टैंडअलोन मोड में इस्तेमाल किया गया था। इस तरह के एक विश्लेषण के लिए मॉडलिंग सिस्टम भूमि भूमि राज्यों के वैध spatiotemporal व्यवहार का उत्पादन करने की आवश्यकता है। लेकिन बेहतर रिज़ॉल्यूशन अवलोकन के साथ एक मोटे रिज़ॉल्यूशन मॉडल सिमुलेशन का मूल्यांकन चुनौतियों का अपना सेट है। इसने सिस्टम के लौकिक गतिशीलता पर आधारित मूल्यांकन मानकों के एक नए सेट की शुरुआत की। एक उपग्रह आधारित मिट्टी की नमी उत्पाद *इन-सीटू* की कमी की वजह से अवलोकन प्रणाली के रूप में इस्तेमाल किया गया था भारत पर माप चूंकि, मॉडल मूल्यांकन से पहले उपग्रहों की अपनी त्रुटि विशेषताओं के लिए भी जाना जाता है, उपग्रह मिट्टी नमी उत्पादों का मूल्यांकन भी किया गया था। इस पर आधारित, थीसिस को तीन व्यापक उद्देश्यों में विभाजित किया गया था: 1. उपग्रह अवलोकन प्रणाली का मूल्यांकन, 2. मॉडलिंग ढांचे का मूल्यांकन, और 3. भूमि सतह को प्रभावित करने वाली वस्तुएँ के Spatiotemporal विकास। ये तीन उद्देश्य इस काम के तीन मुख्य अध्याय हैं, जिन पर नीचे संक्षेप में चर्चा की गई है।

अध्याय 2, भारत से 2010 से 2013 तक एक अतिव्यापी समय अवधि के लिए उपलब्ध उपग्रह मिट्टी की नमी उत्पादों के मूल्यांकन की चर्चा करता है। चार उपलब्ध उपग्रह उत्पादों का मूल्यांकन मिट्टी की नमी रेनालिसिस उत्पाद के साथ आधुनिक युग पुनरावृत्त -विश्लेषण के लिए किया गया था, अनुसंधान और अनुप्रयोग के लिए विश्लेषण एस- लैंड (मेरा एल)। यूरोपीय स्पेस एजेंसी- चैलेंज चेंज इनिशिएटिव (ईएसए-सीसीआई) कार्यक्रम के तत्वावधान में , तीन बहु-दशमांश मिट्टी की नमी डेटासेट सभी उपलब्ध उपग्रह मिट्टी के नमी उत्पादों, जैसे, सभी सक्रिय-मर्ज किए गए उत्पादों को मिलाकर जेनरेट होते हैं: सीसीआई-ए ; सभी निष्क्रिय-विलय उत्पाद: सीसीआई-पी; और सभी सक्रिय-निष्क्रिय-विलय उत्पाद: सीसीआई-सी। उनकी तुलना ईएसए की मृदा नमी महासागर लवणता (एसएमओएस) पीआरोडक्ट के साथ की गई थी। दो- चरण मूल्यांकन रणनीति यहां कार्यरत थी। पहले एक प्रारंभिक समय श्रृंखला और सहसंबंध विश्लेषण के बाद ट्रिपल कोलोशन नामक एक उपन्यास त्रुटि अनुमान पद्धति के बाद किया गया। यह देखा गया था कि भारत भर में एसएमओएस के आरोही स्वस्थ में उतरने की तुलना में अधिक त्रुटि थी, जिसने आगे के विश्लेषण के लिए अवरोही स्वैथ के उपयोग को प्रेरित किया। प्रारंभिक समय दोनों से श्रृंखला और सहसंबंध विश्लेषण और ट्रिपल कोलोकेशन विश्लेषण, यह देखा गया था कि पश्चिमी शुष्क और अर्द्ध शुष्क क्षेत्रों को छोड़कर सक्रिय उपग्रहों का भारत पर उच्च प्रदर्शन होता है। इसके बाद सीसीआई-सी और फिर सीसीआई-पी द्वारा किया गया। एसएमओएस ने बाकी उत्पादों की तुलना में त्रुटि के अपेक्षाकृत उच्च मूल्य दिखाए। हालांकि, चूंकि एसएमओएस ई-सीएसआई उत्पादों की तुलना में एल-बैंड सेंसर है जो सी-बैंड सेंसर से पुनर्प्राप्त किया जाता है, यह भारत के घने वनस्पति क्षेत्रों पर बेहतर प्रदर्शन दिखाता है। इस विश्लेषण के आधार पर, ईएसए-सीसीआई उत्पादों का इस्तेमाल भारत पर मॉडलिंग मिट्टी नमी का मूल्यांकन करने के लिए किया गया था।

अध्याय 3 पद्धति और सीएलएम 4.5 अनुरूपित मिट्टी नमी के प्रदर्शन मूल्यांकन के बाद के परिणामों पर चर्चा करता है। चूंकि, सीएलएम 4.5 को निर्धारित वायुमंडलीय फोर्किंग के साथ स्टैंडअलोन मोड में चलाया जा रहा है, मॉडल सिमुलेशन पर रेनालिसिस वर्षा के प्रभाव की भी जांच की गई थी। दो

पुनर्नवीनीकरण वर्षा उत्पादों का उपयोग किया गया, जैसे सीआरयू-एनसीईपी और मेरा 2। इस अंतर - तुलना विश्लेषण से पता चला कि एमईआरआरए 2 के साथ मजबूर सीएलएम 4.5 का प्रदर्शन बेहतर था। इस प्रकार, एमएलआरए 2 वर्षा के साथ मजबूर होने पर सीएलएम 4.5 की मिट्टी नमी सिमुलेशन का इस्तेमाल मॉडलिंग मिट्टी नमी के अंतिम प्रदर्शन मूल्यांकन के लिए किया गया था। नियोजित निष्पादन मूल्यांकन पद्धति में अस्थायी स्थिरता, ऑटो-सहसंबंध समारोह और ट्रिपल कोलेशन विश्लेषण शामिल हैं। सैद्धांतिक स्थिरता और ऑटो-सहसंबंध फ़ंक्शन विश्लेषण का उपयोग उपग्रह और रीनलिसिस के संबंध में मॉडल द्वारा मनाए गए अनुसार मिट्टी की नमी के स्पीतिओमपोराल गतिशीलता की अनुकूलता को देखने के लिए किया गया था। इस विश्लेषण ने सुझाव दिया है कि CLM4.5 मनाया मिट्टी की नमी की स्थानिक और लौकिक गतिशीलता को हासिल करने में सक्षम है। हालांकि यह ट्रिपल कॉलोकेशन से अनुमानित यादृच्छिक त्रुटि के उच्च मूल्य दिखाता है।

अध्याय 4 मृदा नमी के मकड़ी के विकास और भारत में उथल-पुथल गर्मी के प्रवाह के व्यवहार को दर्शाता है। यह उन्हें समय-परिवर्तनीय, अंतरिक्ष-परिवर्तनीय समय-संस्करण और अंतरिक्ष-भिन्नता समय-संस्करण घटकों में विघटित करके हासिल किया जाता है। ये भूमि सतह राज्यों के व्यवहार पर गतिशील और स्थैतिक कारकों के नियंत्रण से संबंधित हैं। इस प्रकार, तीन विघटित घटकों भूमि सतह राज्यों के spatiotemporal परिवर्तनशीलता पर प्रत्येक नियंत्रक कारक का योगदान देने में सक्षम हैं। यह देखा गया कि भारत में 0.9 डिग्री सेल्सियस 1.25 डिग्री के एक कोरसर रिज़ॉल्यूशन पर, गर्मी की गर्मी की तुलना में अव्यक्त गर्मी प्रवाह में मिट्टी नमी परिवर्तनीयता के लिए एक मजबूत प्रतिक्रिया है। यह भी पाया गया कि दोनों गर्भ धारण और मिट्टी की नमी स्थिर नियंत्रणों से प्रभावित होती है जैसे कि मिट्टी के प्रकार, स्थलाकृति, आदि। हालांकि, समझदार गर्मी पर गतिशील नियंत्रण, वायुमंडलीय स्थिति, भूमि सतह के तापमान, आदि का प्रभाव होता है। इस काम का एक बहु-विविध भूमि डेटा आकलन प्रणाली की व्यवहार्यता की जांच भी करना था। और परिणामों के आधार पर, यह निष्कर्ष निकाला जा सकता है कि भारत जैसे एक स्थानिक रूप से परिवर्तनीय क्षेत्र के लिए, एक बहु-विविध डेटा आकलन प्रणाली सही

तरीका है। यह थीसिस कुछ सुझावों के साथ समाप्त होता है जिस दिशा में इस थीसिस में किए गए काम को लिया जा सकता है।

Contents

<i>Certificate</i>	i
<i>Acknowledgement</i>	ii
<i>Abstract</i>	iv
<i>List of Figures</i>	x
<i>List of Tables</i>	xiv
<i>Abbreviations</i>	xv
1 Chapter 1: Introduction	1
1.1 INTRODUCTION	2
1.1.1 Background	2
1.1.2 Motivation	3
1.1.3 Objectives	5
1.1.4 Description of The Thesis	13
1.1.4.1 Chapter 1: Introduction	13
1.1.4.2 Chapter 2: Evaluation of Observation System	13
1.1.4.3 Chapter 3: Evaluation of Land Surface Modeling System	13
1.1.4.4 Chapter 4: Spatiotemporal Evolution of Land Surface States	14
1.1.4.5 Summary and Conclusion	14
2 Chapter 2: Evaluation of Observation System	15
2.1 INTRODUCTION	16
2.2 DATA	19
2.2.1 ESA-CCI Satellite Soil Moisture Products	21
2.2.2 SMOS Soil Moisture	22
2.2.3 MERRA-Land Reanalysis Soil Moisture	23

2.2.4	IMD Precipitation	24
2.3	METHODOLOGY	24
2.3.1	Pre-processing of Datasets	25
2.3.2	Comparison using Classical Metrics	27
2.3.3	Comparison using $fRMSE_{TC}$	28
2.4	RESULTS AND DISCUSSION	32
2.4.1	Comparison of Ascending and Descending Swath of SMOS	32
2.4.2	Classical Analysis of SM^{RS} Products	33
2.4.2.1	Seasonality	33
2.4.2.2	Correlation Analysis of Satellite Soil Moisture	37
2.4.3	Comparison of Soil Moisture $fRMSE_{TC}$ Estimates	40
2.5	SUMMARY AND CONCLUSION	47
3	<i>Chapter 3: Evaluation of Land Surface Modeling System</i>	51
3.1	INTRODUCTION	52
3.2	DESCRIPTION OF MODELING SYSTEM AND DATASETS	56
3.2.1	Description of Modeling System	56
3.2.2	CRUNCEP Precipitation	57
3.2.3	MERRA2 Precipitation	58
3.3	METHODOLOGY	59
3.3.1	Model Setup	59
3.3.2	Pre-processing of Datasets	63
3.3.3	Inter-comparison of Modeling System Forced with Different Precipitation Forcings	64
3.3.4	Evaluation of Modeling System	65
3.4	RESULTS AND DISCUSSION	69

3.4.1	Inter-comparison Analysis	69
3.4.2	Evaluation of CLM45 Simulated SM	79
3.5	SUMMARY AND CONCLUSION	86
4	<i>Chapter 4: Spatiotemporal Evolution of Land-Surface States</i>	90
4.1	INTRODUCTION	91
4.2	DATA DESCRIPTION AND METHODOLOGY	94
4.2.1	Description of Simulated Soil Moisture and Heat Fluxes	94
4.2.2	Spatiotemporal Variability Analysis	94
4.3	RESULTS AND DISCUSSION	97
4.3.1	Time series and Temporal Stability Analysis	98
4.3.2	Spatiotemporal Decomposition	103
4.4	SUMMARY AND CONCLUSION	107
5	<i>Chapter 5: Summary and Conclusion</i>	110
5.1	SUMMARY AND CONCLUSION	111
5.2	FUTURE WORK	115
5.3	COLLABORATIONS	116
	<i>References</i>	117
	<i>Curriculum Vitae</i>	137

List of Figures

1.1	<i>Spatial distribution of soil moisture-precipitation coupling strength (June-July-August), averaged across AGCMs</i>	4
1.2	<i>The workflow followed in this thesis is presented here as a flowchart</i>	12
2.1	<i>Workflow of the evaluation methodology employed in this study</i>	26
2.2	<i>Difference between $fRMSE_{TC}$ of SMOS-A and SMOS-D</i>	33
2.3	<i>Seasonality of SM distributions (SMOS-D, CCI-ACT, CCI-PAS, CCI-COMBINED, MERRA-L) and IMD precipitation, averaged over India</i>	35
2.4a	<i>Four year average [2010-2013] of MODIS-Terra NDVI values over India</i>	36
2.4b	<i>Average probability of RFI occurrences in the SMOS L-band measurements for the period 2010—2012</i>	36
2.5	<i>Annual mean seasonality of SM for CCI-ACT, CCI-PAS, CCI-COMBINED, SMOS-D and MERRA-L</i>	37
2.6	<i>Pearson correlation ($p < 0.05$) between the SM^{RS} (CCI-ACT, CCI-PAS, CCI-COMBINED and SMOS-D) and MERRA-L reanalysis SM (original and anomaly)</i>	38
2.7	<i>Fig. 2.7. Spearman correlation ($p < 0.05$) between SM^{RS} (CCI-ACT, CCI-PAS, CCI-COMBINED and SMOS-D) and IMD precipitation (original and anomaly)</i>	40
2.8	<i>$fRMSE$ of SM^{RS} (CCI-ACT, CCI-PAS, CCI-COMBINED and SMOS-D)</i>	41
2.9	<i>Köppen-Geiger climate classification updated map</i>	43
2.10	<i>FAO's Sand, Silt and Clay percentage maps</i>	44
2.11	<i>Effect of percentage of Sand, Silt and Clay and NDVI on $fRMSE^{TC}$. Dashed</i>	46

	<i>lines are the respective trend lines</i>	
2.12	<i>Percentage contribution of percentage of sand, silt, and clay and NDVI on f_{RMSE} of CCI-ACT, CCI-PAS, CCI-COMBINED and SMOS-D</i>	47
3.1	<i>Schematic representation of evolution of land surface models</i>	55
3.2	<i>Scatter plot of all-India average (a) rainfall, and (b) surface temperature (TS) from CRU-NCEP and MERRA2</i>	62
3.3	<i>Yearly SM for 55 years of spin-up for the year 2002 using two precipitation forcings from (a) CRUNCEP and (b) MERRA2</i>	62
3.4	<i>Workflow of the methodology employed in this chapter</i>	68
3.5	<i>Spatial distribution of rainfall seasonality for different seasons (JF: Winter; MAM: Pre-monsoon; JJAS: Monsoon; and OND: Post-monsoon) of IMD, CRUNCEP, and MERRA2 (mm/day)</i>	70
3.6	<i>Time series of rainfall seasonality of IMD, CRU-NCEP, and MERRA2</i>	70
3.7	<i>Yearly time series of box-whisker plot of monthly rainfall of IMD, CRU-NCEP, and MERRA2</i>	71
3.8	<i>Monthly time series of all-India average rainfall for major climate zones of India (based on Koppen-Geiger climate classification map)</i>	72
3.9	<i>Monthly evolution of spatial standard deviation of rainfall</i>	73
3.10	<i>Statistically significant ($p < 0.05$) spearman rank correlation coefficient of CRUNCEP vs. IMD and MERRA2 vs. IMD for the original and anomaly time series</i>	74
3.11	<i>Soil moisture seasonality of CCI-C, CLM-CRUNCEP, CLM-M2, and MERRA-L</i>	74
3.12	<i>Box-whisker plot of all-India average monthly soil moisture fields</i>	75

3.13	<i>SM time series of CCI-C, CLM-CRUNCEP, CLM-M2, and MERRA-L</i>	75
3.14	<i>Monthly time series from 2003 of CCI-C, CLM-CRUNCEP, CLM-M2, and MERRA-L in different climatic zones</i>	77
3.15	<i>Monthly evolution of spatial standard deviation of soil moisture</i>	77
3.16	<i>Statistically significant ($p < 0.05$) spearman correlation coefficient between different SM datasets</i>	78
3.17	<i>Measures of temporal stability: (a) Mean Relative Difference (MRD) and (b) Standard Deviation of Relative Difference (SDRD)</i>	80
3.18	<i>Auto-Correlation Function (ACF) of CLM4.5 soil moisture, MERRA-Land soil moisture and CCI-C soil moisture; (a) original time series ACF, (b) anomaly time series ACF</i>	82
3.19	<i>Auto-Correlation Function at different lag-times for CCI-C, CLM-M2, and MERRA-L for different climate classification zones</i>	82
3.20	<i>Spatial distribution of C_{Lag} for CCI-C, CLM-M2, and MERRA-L</i>	83
3.21	<i>The difference in characteristic lag-time (C_{Lag}) of two data pairs, (a) CLM-M2 - CCI-C; (b) CLM-M2 – MERRA-L</i>	84
3.22	<i>RMSE_{TC} estimate for CCI-A, CCI-P, CLM-M2, CLM-CRUNCEP, and MERRA-L soil moisture</i>	86
4.1	<i>Inter-comparison of time series of all-India average of CLM45 simulated (a) CLM45 SHF and MERRA-L SHF; (b) CLM45 LHF and MERRA-L LHF</i>	98
4.2	<i>Time series of all-India average CLM45 simulated SM, SHF, and LHF</i>	99
4.3	<i>Time series inter-comparison of LHF, SHF, and SM for different climate classes over India</i>	101
4.4	<i>Spatial plots of MRD values of SHF, LHF, and SM over India</i>	102
4.5	<i>Temporal evolution of percentage contribution of different components of</i>	105

	<i>spatiotemporal distribution of SM at three different soil depths (a) Layer-1: 0-3cms; (b) Layer-2: 3-20cms; Layer-3: 20-100cms</i>	
4.6	<i>Time series of components of spatial variance of (a) SM, (b) SHF and (c) LHF</i>	106

List of Tables

2.1	<i>Description of the SM data products</i>	20
2.2	<i>Median of spatially distributed Spearman's and Pearson's correlation coefficients for the different SM^{RS} members</i>	40
2.3	<i>The major climate classes over India and respective mean $fRMSE_{TC}$ values of the satellite products</i>	43
2.4	<i>Description of the homogeneous climate classes</i>	43
3.1	<i>Major climatic zones of India based on climate classes</i>	72
3.2	<i>Spearman rank correlation of MRD of CLM-M2 vs. CCI-C and CLM-M2 vs. MERRA-L</i>	81
4.1	<i>Major climatic zones of India based on climate classes given by Kottek et al. (2006)</i>	100
4.2	<i>Rank correlation of MRD values of two data pairs (SM vs. SHF and SM vs. LHF)</i>	102
4.3	<i>Statistically significant correlation coefficient of contribution of static and dynamic factor on the spatial variance of SM, SHF, and LHF</i>	106

Abbreviations

<i>SM</i>	<i>Soil Moisture</i>
<i>SHF</i>	<i>Sensible Heat Flux</i>
<i>LHF</i>	<i>Latent Heat Flux</i>
<i>DA</i>	<i>Data Assimilation</i>
<i>LST</i>	<i>Land Surface Temperature</i>
<i>CLM45</i>	<i>Community Earth System Model version-1.2.0-Community Land Model version-4.5</i>
<i>ESA-CCI</i>	<i>European Space Agency's – Climate Change Initiative</i>
<i>CCI-A/CCI-ACT</i>	<i>A merged product of all active C-band satellite soil moisture products</i>
<i>CCI-P/CCI-PAS</i>	<i>A merged product of all passive C-band satellite soil moisture products</i>
<i>CCI-C/CCI-COMBINED</i>	<i>A merged product of all active and all passive C-band satellite soil moisture products.</i>
<i>TC</i>	<i>Triple Collocation</i>
<i>RMSE_{TC}</i>	<i>Root Mean Square Error estimated using Triple Collocation</i>
<i>MLR</i>	<i>Multiple Linear Regression</i>
<i>LSM</i>	<i>Land Surface Model</i>
<i>CRUNCEP</i>	<i>Climate Research Unit-National Centers for Environmental Prediction</i>
<i>MERRA2</i>	<i>Modern Era Retrospective-analysis for Research and Application version-2</i>
<i>MERRA-L</i>	<i>Modern Era Retrospective-analysis for Research and Application-Land</i>
<i>CLM-CRUNCEP</i>	<i>CLM45 forced with CRUNCEP rainfall forcing</i>
<i>CLM-M2</i>	<i>CLM45 forced with MERRA2 rainfall forcing</i>
<i>MRD</i>	<i>Mean Relative Difference</i>

<i>SDRD</i>	<i>Standard Deviation of Relative Difference</i>
<i>RD</i>	<i>Relative Difference</i>
<i>TS</i>	<i>Temporal Stability</i>
<i>ACF</i>	<i>Auto-Correlation Function</i>
<i>THF</i>	<i>Turbulent Heat Flux</i>
<i>SSM</i>	<i>Satellite Soil Moisture</i>
<i>SMOS</i>	<i>Soil Moisture Ocean Salinity</i>
<i>IMD</i>	<i>India Meteorological Department</i>
<i>fRMSE_{TC}</i>	<i>fractional-RMSE using Triple Collocation</i>
<i>RFI</i>	<i>Radio Frequency Interference</i>
<i>NDVI</i>	<i>Normalized Difference Vegetation Index</i>
<i>LDAS</i>	<i>Land Data Assimilation System</i>
<i>IC</i>	<i>Initial Condition</i>
<i>CPC</i>	<i>Climate Prediction Center</i>
<i>CMAP</i>	<i>CPC merged Analysis Precipitation</i>