Chapter 7

Summary, major conclusions and future scope

7.1 SUMMARY AND MAJOR CONCLUSIONS OF THE THESIS

Monitoring the terrestrial surface and understanding land surface processes with the help of satellite derived LSPs are of prime importance in understanding climate system. In order to fulfil such goal, efforts have been made in this thesis by raising three key questions at the beginning of the thesis,

(1) What is the influence of the scene-sensor factors on the LSP retrieval?

(2) How are the LSPs and atmospheric variables retrieved from the satellite data?

(3) What is the role of the LSPs in the land surface processes?

A systematic study involving satellite data, RT models and field experiments was carried out with the following four major objectives,

(1) To understand and quantify the impact of atmosphere-sensor characteristics on the land surface parameters,

(2) To derive atmospheric variables (Rayleigh, aerosol, water vapour optical thickness) required in the retrieval of land surface parameters,

(3) To develop the framework and techniques for the retrieval of land surface parameters (surface reflectance, NDVI, LAI, NPP) from the satellite data, and

(4) Use of surface parameters and process based model to understand the land surface processes in land-atmosphere interactions.

Following major conclusions could be drawn from the thesis,

1. The influence of the atmospheric constituents namely, columnar water vapour, ozone content, aerosol optical thickness and Rayleigh molecules on the IRS measurements was quantified using an atmospheric RT model. The impact of atmospheric variables found to be significant of the order of 0.12 to 11.27% (relative deviation) for water vapour, 3.80 to 9.16% for ozone, while an absolute deviation of 0.006 to 0.094 in reflectance
due to the aerosol, which translates an effect of 0.03 to 0.23 in NDVI. These estimates are reported first time for IRS sensors and could be useful to IRS user community.

2. Significant differences in spectral characteristics were observed amongst IRS sensors, where $\lambda_c$ varied from 4 nm to 14 nm and $\Delta \lambda$ varied from 1.6 nm to 14.07 nm. A variation within the $E_0$ for green to SWIR bands for various IRS sensors could induce uncertainties in TOA reflectance of the order of 0.92% to 3.35%. Significant effect of SRF on the measurements of surface reflectance and NDVI by various IRS sensors was observed for vegetation target. The relative differences in red and NIR reflectance were of the order of 3.38% and 0.9% respectively, while the absolute differences were $-0.09$ to 0.13 and 0.014 to 0.43 respectively for these bands. This study illustrated that the influence of differences in sensor spectral response on the estimation of surface reflectance and NDVI are significant enough to be taken into account, when comparable measurements of satellite sensors for long-term monitoring of the Earth’s environment are required.

3. The analysis with the off-nadir observations in IRS channels showed a variation of 3-24%, 2-9% and 5-6% in reflectance for red, NIR and panchromatic bands respectively of the spectrum. The quantification of anisotropic factor (g-factor) carried out in the study would be useful in deriving nadir to off-nadir convertibility and in the hemispherical integration for all the view angles in radiance to flux conversion for broad band sensors. This study provided a new approach of coupling biophysical and atmospheric RT models, which simulates at-sensor directional reflectances in IRS spectral bands.

4. Approaches based upon satellite data, theoretical modelling and field measurements were proposed to estimate the important atmospheric variables namely, (1) Rayleigh optical thickness, (2) aerosol optical thickness and (3) atmospheric water vapour. The Rayleigh optical thickness for the sensors flown on IRS-1B, 1C, 1D, P4 and P6 are reported in this study. As there are a number of international ground stations currently receiving the data of IRS satellites, the reported values will be of interest to a wider set of global scientific community.

5. A new method of retrieving the AOT was proposed in the study. This method used dual-view angle capability of the satellite data and the forward atmospheric simulations to
arrive at a property called a cross over reflectance \((p_{co})\). The systematic shift in the position of this \(p_{co}\) was used to derive AOT for a scene, given other atmospheric conditions being constant. The AOT was estimated for two sites representing clear and turbid atmospheric conditions. Comparison of AOT estimates was carried out using the MODIS AOT products, which showed a very good agreement.

6. Atmospheric water vapour was estimated using a differential absorption technique. This technique makes use of the satellite radiance in a suitably chosen water vapour absorption band and a band where water absorption is negligible. The approach accounts for the land cover class information of that region. Validation of the water vapour derived from satellite data was also carried out to the ground measurements collected synchronous to satellite pass.

7. A method of retrieving the fundamental surface property – surface reflectance was proposed by modifying the atmospheric 6S-RT model for the IRS sensors. The satellite-derived reflectance was validated with the field measurements of spectroradiometer, which showed a very good agreement with an RMSE of 9-14 percent. This study was an attempt to fill the gap of deriving surface reflectance from IRS data, which would be useful in many applications.

8. A method and algorithm was developed to derive other very important surface parameter – NDVI from the geostationary platform. This algorithm provides a major advantage to its derived fields over traditional reflectance or NDVI fields in a sense that it incorporates sensor characteristics such as, spectral response function in derivation of Exo-atmospheric solar irradiance \((E_0)\), Rayleigh optical thickness, Ozone optical thickness and viewing geometry in deriving atmospheric contribution to radiance. The analysis showed a significant improvement in the derived products as compared to uncorrected product and comparison with SPOT-NDVI showed a very good agreement.

9. Basic framework and methodology was developed to retrieve the vegetation surface parameter – LAI from IRS LISS-III data for two sites in Central India. The IRS derived LAI was used as a reference to validate the version 3 and 4 MODIS LAI product, which showed a significant positive correlation \((r=0.62\) to 0.78). However, an overestimation
was observed for the version 3 MODIS LAI product (by a factor of 1.16 to 2.5) when compared with the LISS-III derived LAI with an RMSE of 0.20 to 1.26. The factor of overestimation decreased significantly by 50% and RMSE reduced by 40% when version 4 was analyzed and compared to LISS derived LAI. Efforts were made to understand the cause of overestimation in the MODIS LAI product in terms of algorithm applied in different versions, choice of compositing period and land cover used for the classification of the study area.

10. A land surface model (LSM) was used to understand the land surface processes over a crop site in the semi arid region of western part of the India. Remote sensing derived surface parameters like reflectance, NDVI, LAI etc were used as inputs to the LSM. The parameterization of the atmospheric forcing variables was presented and numerical simulations of various surface fluxes were performed on the diurnal basis. Moreover, NPP of the study grid was estimated from the satellite data using the PEM method. The LSM generated energy fluxes in terms of $R_n$ were validated with the field measured $R_n$, which showed a good agreement ($R^2$ of 0.98, RMSE of 15.9 Wm$^{-2}$). When NPP derived from the LSM was compared with the satellite derived NPP, a close match was found ($NPP \sim 5.542 \, \text{gC m}^{-2} \, \text{day}^{-1}$) over the study grid under a specific radiation scenario. The impact of LAI on the fluxes was inferred by simulating surface fluxes as a function of LAI. The influence of increasing LAI from 1 to 6 was found to increase the photo-synthesis and in turn enhancing the NPP from 206 to 423 $\mu$gC m$^{-2}$ s$^{-1}$. On the other hand increase in the LAI showed swelling of the canopy evapotranspiration, which in turn increased the latent heat flux and decreased the sensible heat flux and the ground temperature by 4K. Understanding land surface processes through the LSM provided an appreciation of the land-atmosphere interactions, which has an important role in the climate system.

7.2 SCIENTIFIC CONTRIBUTION OF THE STUDY

In this thesis, methods to retrieve and validate the land surface parameters namely, (1) surface reflectance ($\rho$), (2) NDVI, (3) LAI and (4) NPP from the satellite data are reported using empirical and physical methods involving RT models and field experiments. The retrieved land surface parameters were validated with \textit{in-situ} measurements or other
contemporaneous global satellite measurements. Such land surface parameters were used as input to the land surface model (LSM) to understand the land surface processes over a crop site in the semi-arid region of India. Role of an important surface parameter, LAI on the surface fluxes and land-atmosphere interaction was understood with the LSM.

Moreover, the influence of scene-sensor factors on land surface parameters particularly for the IRS channels have been quantified first time and reported in this thesis. Since numerous users are utilizing IRS data across the globe, such estimates could be very useful to the user community. Furthermore, when multi-sensor, multi-temporal data are required to be used for the long-term data analysis to answer some of the science questions, effect of sensor or atmosphere must be normalized. The spectral corrections and atmospheric normalization procedures provided in the thesis are valuable in such studies.

Novel techniques to retrieve the atmospheric variables over land reported in the thesis are vital in atmospheric correction procedure to know accurately the land surface parameters.

Various approaches developed to retrieve the land surface parameters from the Indian Earth Observation Sensors are first of their kind and are reported in the thesis. Particularly, retrieval of surface reflectance by modified atmospheric correction model for IRS sensors, generation of NDVI fields over India from the geostationary platform and the retrieval of LAI fields from the IRS data are of great importance. The algorithm for generating NDVI product from the geostationary platform (sensor INSAT 3A CCD) is being adopted by the ISRO team as an operational product for the India Meteorological Department. As far as contribution of this thesis to the remote sensing community is concerned, major one is the validation of the MODIS LAI product over India. Results of our study on the estimation of LAI from the IRS data have been considered as a reference results to validate the MODIS LAI product over India by the scientific group of Boston University and NASA working on MODIS LAI products.

Results from the thesis have been published in peer-reviewed journals (4 papers), proceedings of symposia (4) and chapter in the book (1). The list of the publications during the course of the research work is provided at the end of the thesis.
7.3 FUTURE SCOPE

The quantification of atmosphere-sensor influences for the IRS channels discussed in the thesis will be utilized for normalizing or comparing multi-sensor/temporal data and generating long-term data series. This also leads to the possibility of implementing various level of atmospheric corrections such as, level L0: converting DN to TOA reflectance, L1: Rayleigh corrected reflectance, L2: Rayleigh, ozone and WV corrected reflectance and L3: full atmospheric correction. Such understanding would be useful in generating future scientific requirement for the spectral channels of Atmospheric Correction Sensor (ACS) for the visible-NIR data. Moreover, satellite sensors having multi-angle (MISR), polarization (POLDER-PARASOL) or LIDAR (CALIPSO) capability need to be explored for more understanding of atmospheric characteristics from the same satellite platform like ACS.

Assimilation of more land surface parameters such as land surface temperature, soil moisture, fraction vegetation cover etc in to the LSM should be carried out. In order to retrieve such surface parameters, state-of-art satellite based instruments with multi-angle viewing capability (MISR, AATSR), hyperspectral imaging (Hyperion) and thermal channels (ASTER, AATSR, MODIS) could be used along with better retrieval techniques.

Understanding the thermal radiance/emissivity spectra from land surface through field-observations (using hand held Fourier Transform based IR-FTIR Spectroradiometer) and RT simulations (using MODTRAN) along with the scene-sensor issues involved in the thermal remote sensing are the challenging areas for the future research.

In the present study, LSM simulations were carried out over crop site in a semi arid region, in future LSM simulations would be carried out for various land covers and on different sites having diverse vegetation functional properties to better understand exchange of the biogeochemical fluxes. Efforts are required for the better representation of vegetation in the LSM instead of static look-up-table through an integrated biosphere simulator (IBIS) model or by Dynamic Vegetation Model (DVGM), which performs integrated assessments of water balance, carbon balance, and vegetation structure on both global and regional scales.