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A linear programming (LP) approach to the retrieval of hyperspectral infrared emissivity

28th June 2018

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Overview of the presentation

Retrieval of hyperspectral infrared surface emissivity

1. PWLR (machine learning) trained against the CAMEL atlas

2. Experimental LP approach intended as a possible new training target for the PWLR
   - Use of hyperspectral measurements for better characterization of spectral features
   - **Key idea**: representation of emissivity as a **convex combination** (linear combination where all coefficients are non-negative and sum to 1) of a set of laboratory spectra

3. A first look at the results
   - Comparison with CAMEL
   - Retrievals over sea

4. Conclusions and outlook

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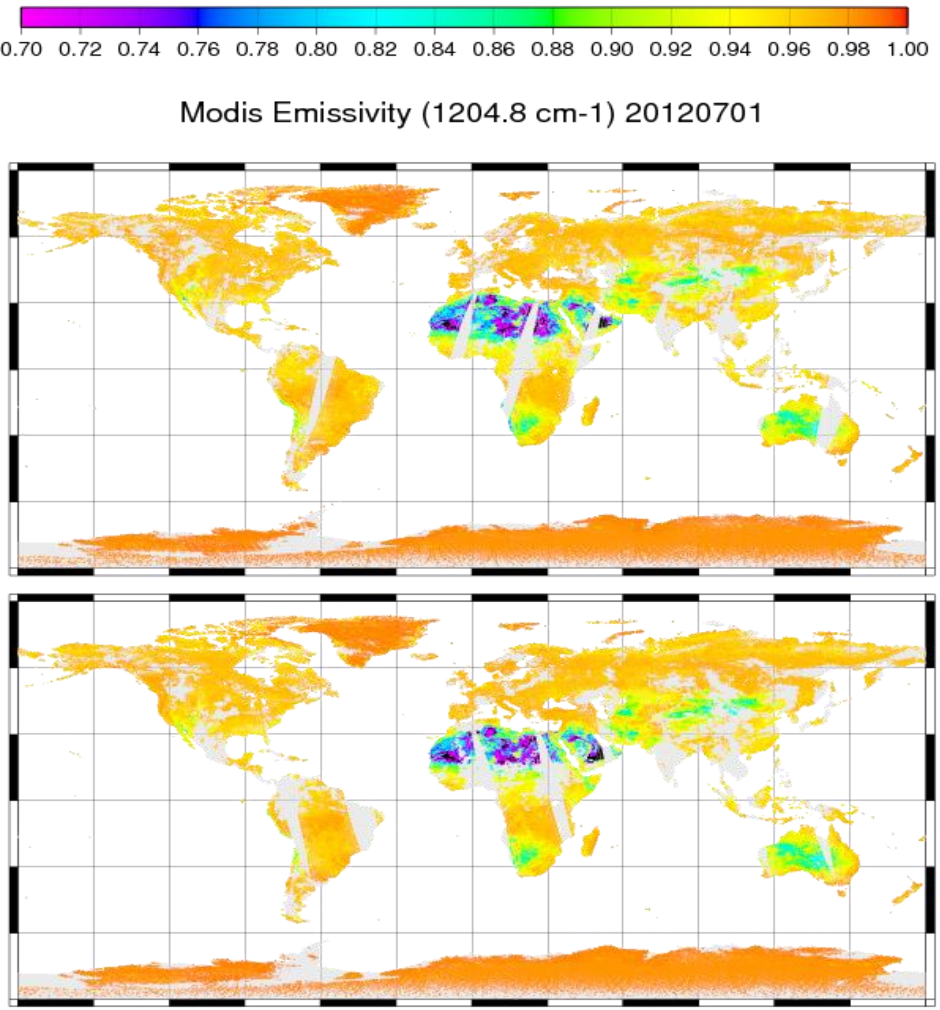
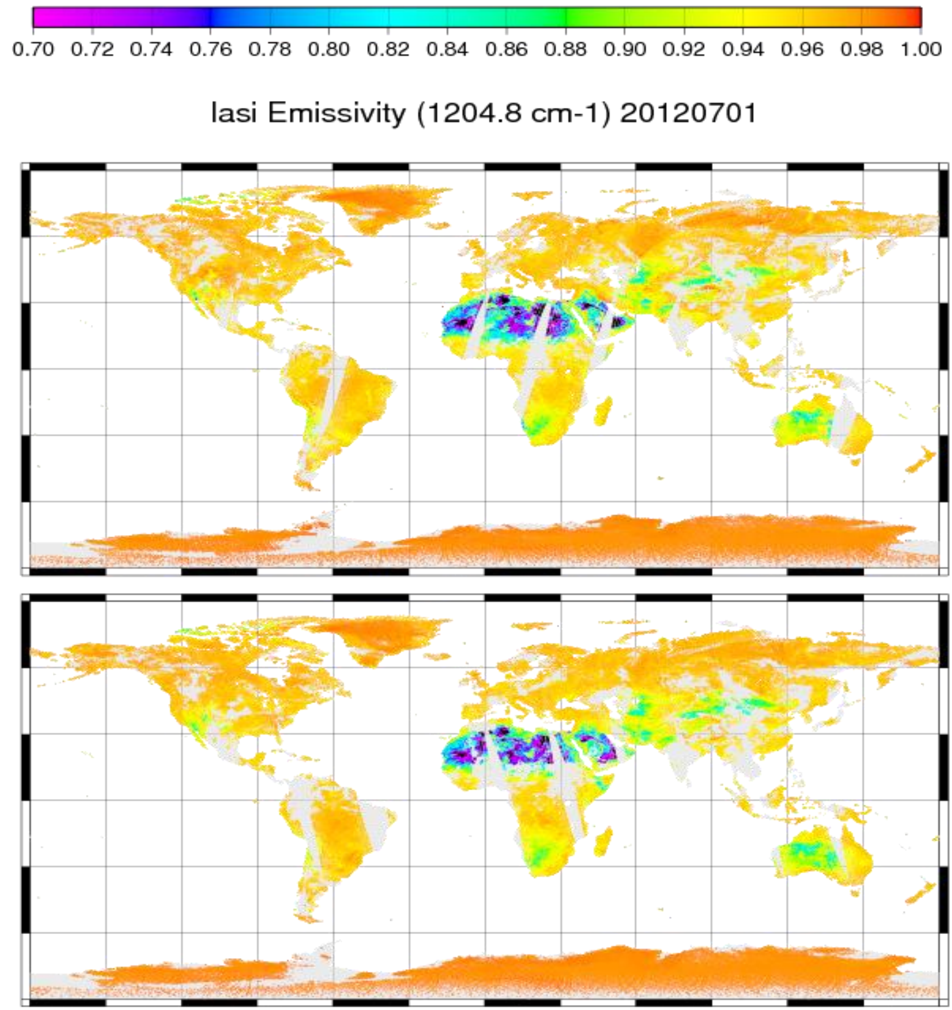
IASI L2 Emissivity (PWLR trained with CAMEL atlas)

Atlas for training



→ Retrieval



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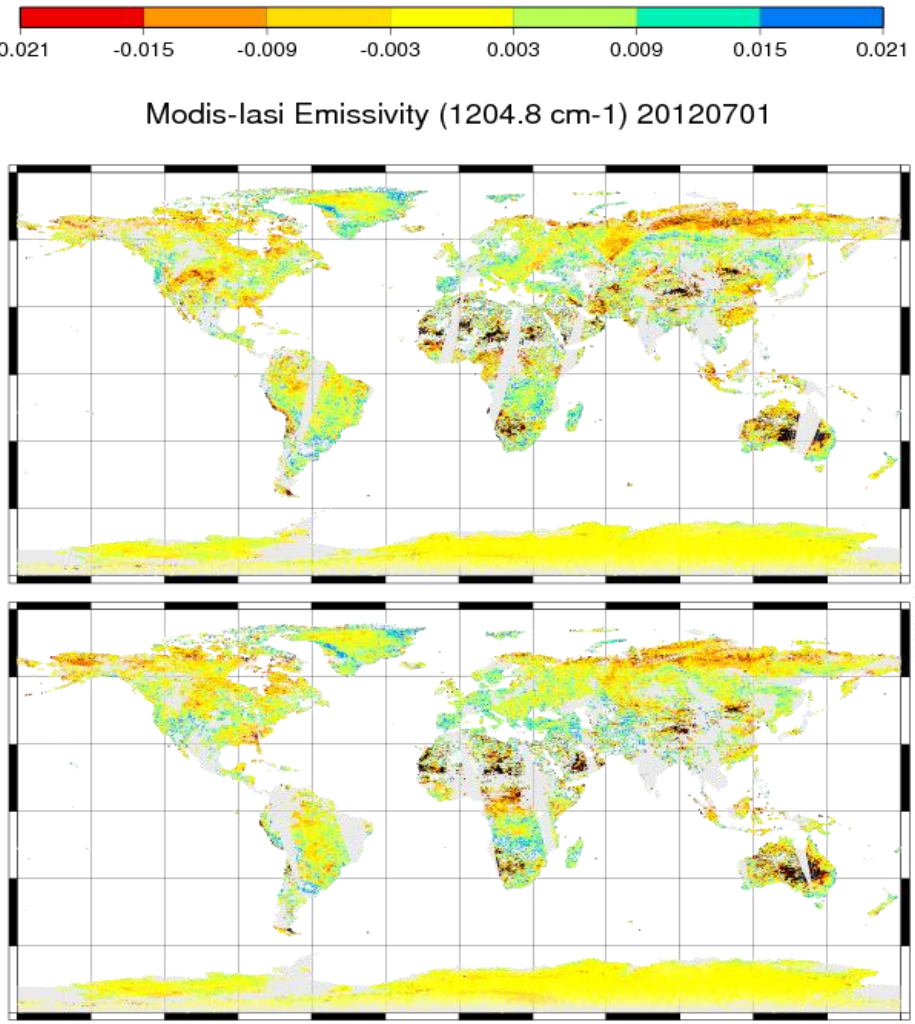
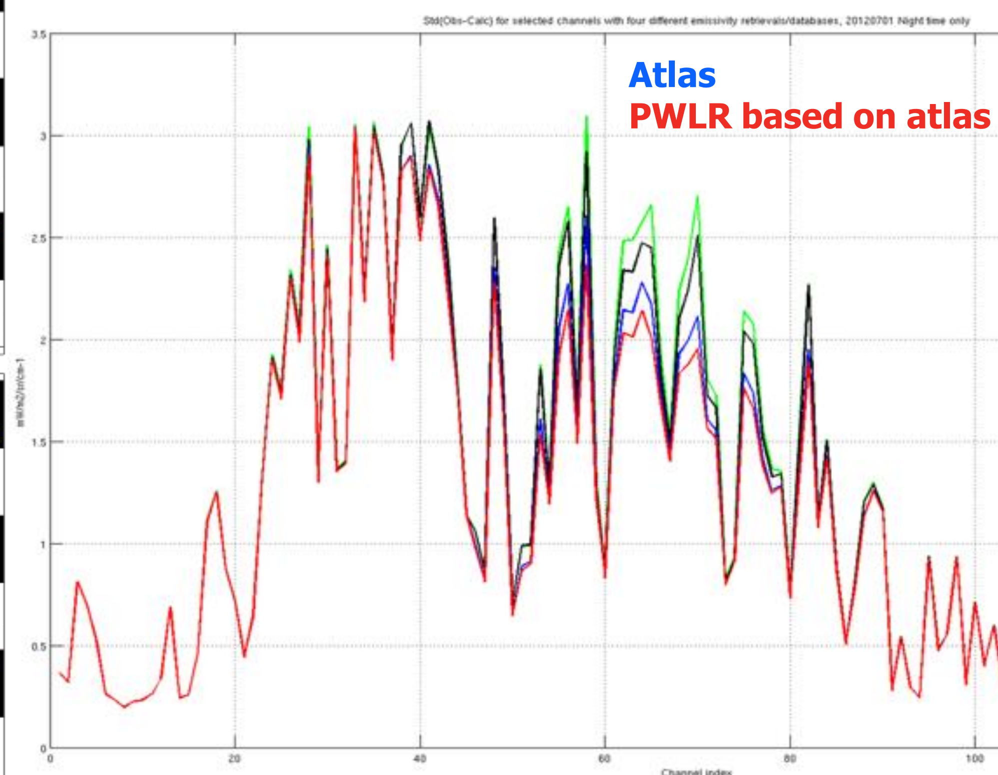
Emissivity difference wrt training atlas

Consistent differences between PWLR retrieval and training atlas day and night



Analysis of obs – calc for different sources of emissivity sources shows that the retrieval is able to improve upon the atlas

Standard deviation of residual (obs minus calc)



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FLOPC++ (Formulation of Linear Optimization Problems in C++)

An open source algebraic modelling language implemented as a C++ class library

- Using FLOPC++, linear optimization models can be specified in a declarative style, similar to algebraic modelling languages such as GAMS and AMPL, within a C++ program. As a result the traditional strengths of algebraic modelling languages are preserved, while embedding linear optimization models in software applications is facilitated.
- FLOPC++ can be used as a substitute for traditional modelling languages, when modelling linear optimization problems, but its principal strength lies in the fact that the modelling facilities are combined with a powerful general purpose programming language. This combination is essential for implementing efficient algorithms (using linear optimization for subproblems), integrating optimization models in user applications, etc.
- FLOPC++ is part of the Computational Infrastructure for Operations Research (COIN-OR) and uses its Open Solver Interface (Osi), which provides an abstract base class to a generic linear programming (LP) solver, along with derived classes for specific solvers. For the emissivity retrievals we have used the **C**OIN-OR **L**inear **P**rogramming (Clp) simplex solver.

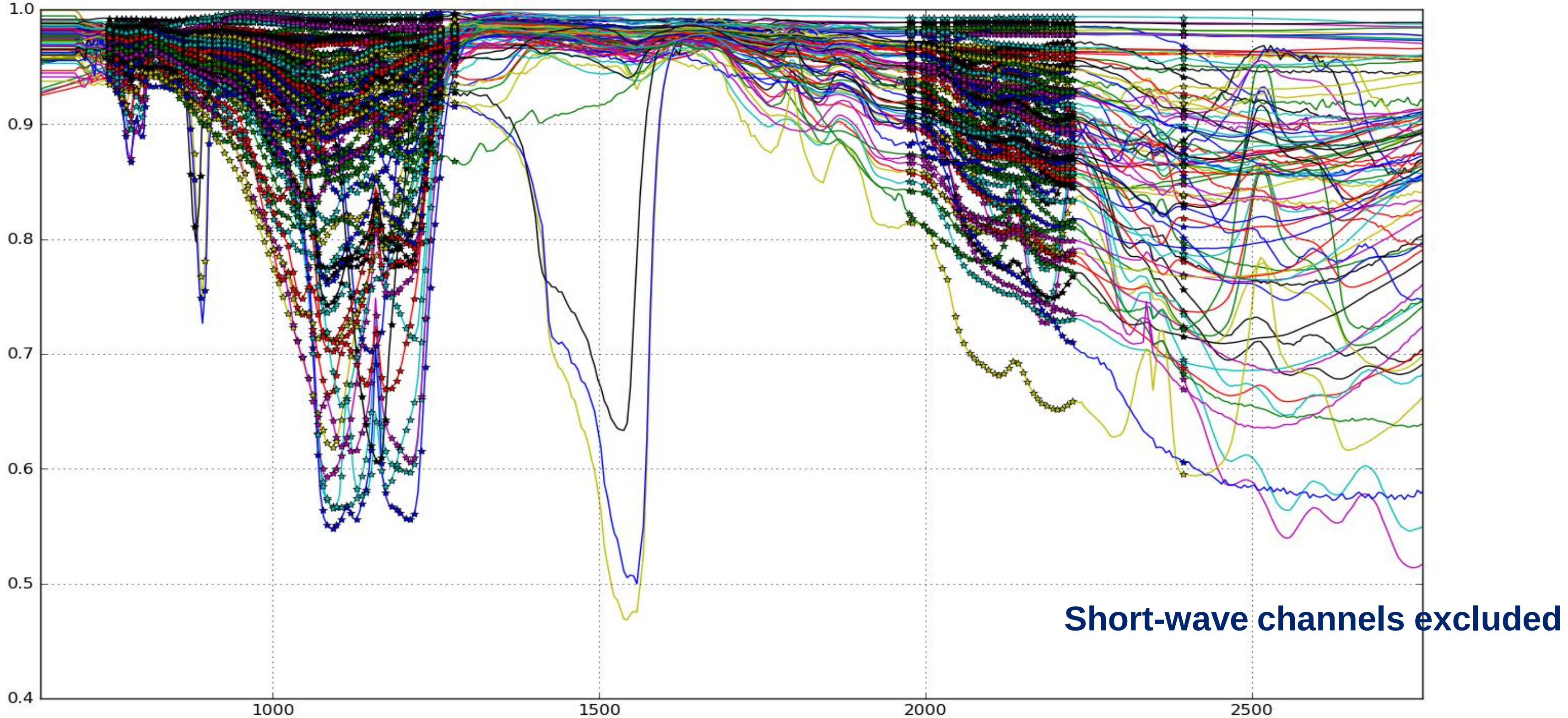
FLOPC++ model for retrieval of skin temperature and emissivity

```
class EmissivityLPModel : public MP_model {
  MP_set I; // Channels
  MP_set J; // Base emissivity spectra

  // Input data
  MP_data Y;        // Measured (reconstructed) radiance
  MP_data W;        // Cost function weights

  MP_data Ts_0;     // First guess surface skin temperature
  MP_data Lambda_0; // First guess emissivity base spectra mix

  MP_data F_0;      // Forward model radiances from first guess
  MP_data Ke;       // Derivative of radiance wrt emissivity
  MP_data KTs;      // Derivative of radiance wrt surface skin temperature

  MP_data E;        // Collection of base emissivity spectra

  // Derived data
  MP_data Klambda;  // Derivative of radiance wrt lambda

  MP_variable ts;    // Retrieved surface skin temperature
  MP_variable lambda;// Weight of each base spectrum in retrieved emissivity
  MP_variable f;     // Forward model radiances (determined by ts and lambda)
  MP_variable abs_error; // Absolute value of the radiance residuals

  MP_constraint forward_model;
  MP_constraint error_def_pos;
  MP_constraint error_def_neg;
  MP_constraint balance; // Ensure that emissivity weights sum up to one

  EmissivityLPModel(int numChannels, int numBase) :
    MP_model(new OsiClpSolverInterface), I(numChannels), J(numBase),
    Y(I), W(I), Lambda_0(J), F_0(I), Ke(I), KTs(I), E(J,I), Klambda(I,J),
    lambda(J), f(I), abs_error(I), forward_model(I), error_def_pos(I), error_def_neg(I)
  {
    Klambda(I,J) = E(J,I) * Ke(I);

    forward_model(I) =  f(I) == F_0(I) + KTs(I)*(ts() - Ts_0()) + sum(J, Klambda(I,J)*(lambda(J)-Lambda_0(J)));

    error_def_pos(I) =  abs_error(I) >= Y(I) - f(I);
    error_def_neg(I) =  abs_error(I) >= f(I) - Y(I);

    balance =  sum(J, lambda(J)) == 1;

    lambda.upperLimit(I) = 1;

    setObjective( sum(I, W(I) * abs_error(I)));
  }
};
```

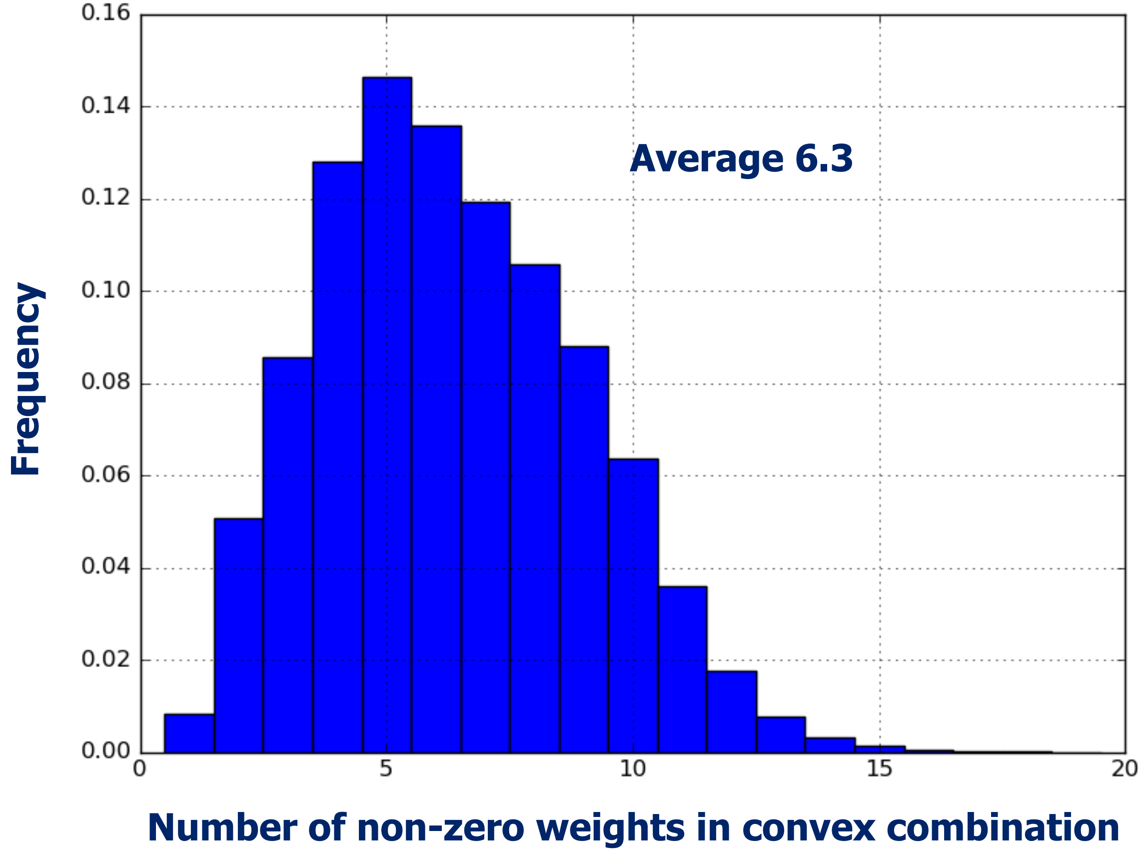
Configuration

95 base emissivity spectra (82+4 from the CAMEL HSR set + plus 9 sea surface emissivity spectra)

102 (surface sensitive) channels



Compactness of representation



Only non-zero "lambdas" need to be kept (sparse representation).

Which profiles to use?

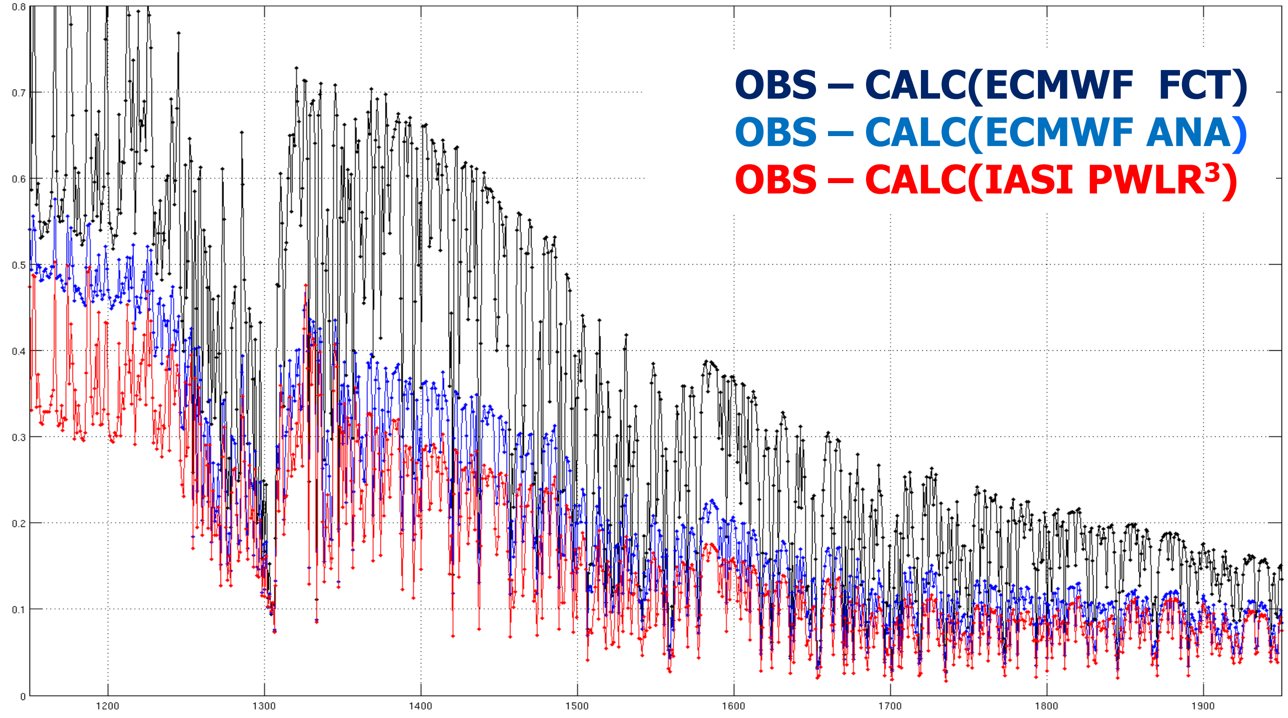
Temperature, water vapour and ozone profiles are needed to feed the forward model.

Errors in the profiles might result in errors in the retrieved emissivity.

NWP forecast/analysis not the best (representativeness errors)

1Dvar retrieved profiles carry information about the assumed emissivity

➔ Use PWLR profiles retrieved without any assumptions about emissivity



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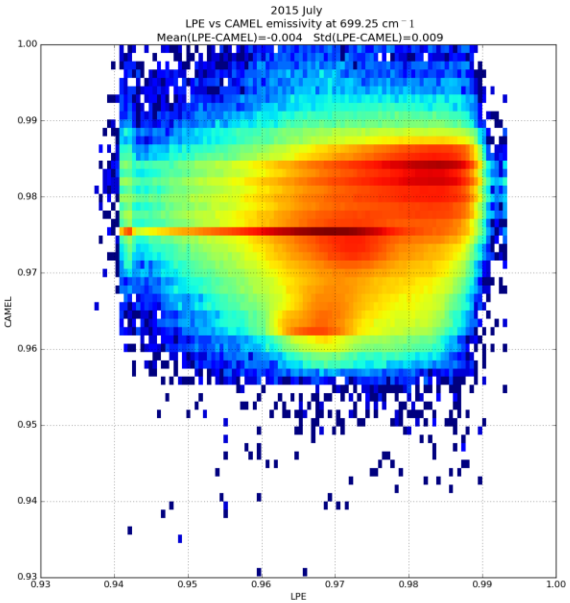
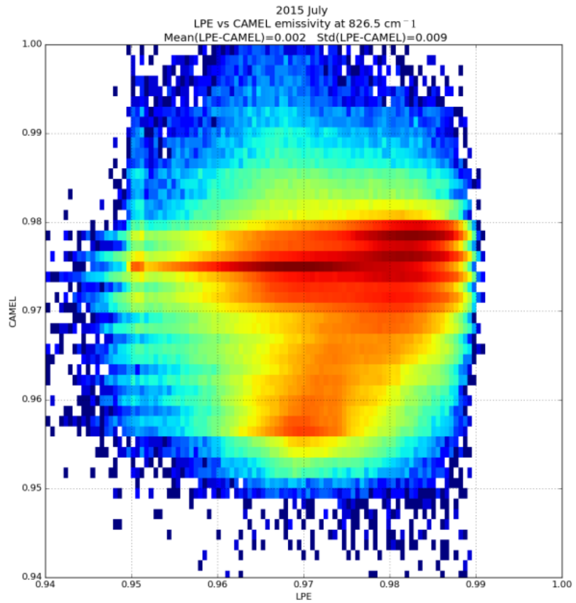
Comparison with CAMEL

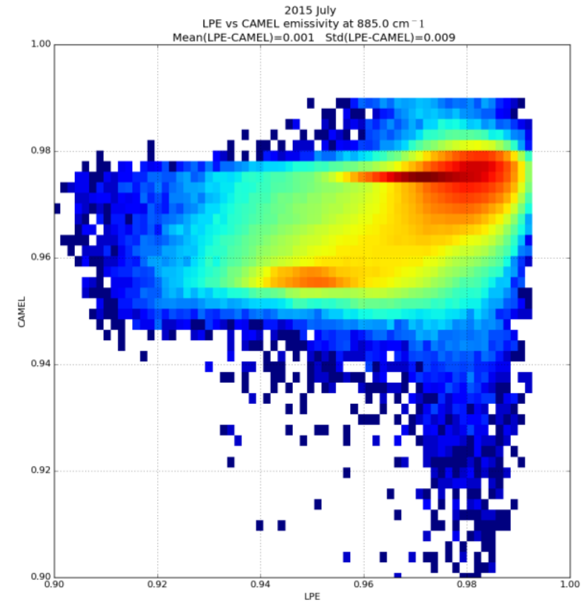
CAMEL 13 hinge points monthly mean emissivity for 2015
MEaSUREs CAMEL Emissivity Product V001

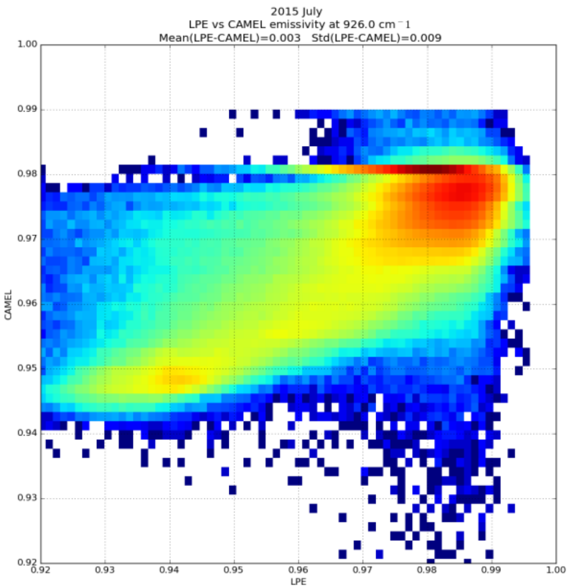
The LP emissivity algorithm was applied to all clear (based on the PWLR cloud signal) IASI fields of view from 2015 over land and sea

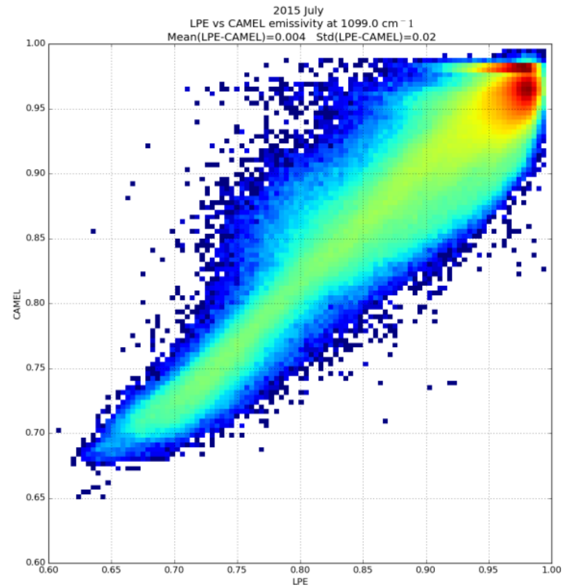
The retrieved "lambdas" were gridded with temporal resolution of one month and spatial resolution of 0.1 times 0.1 degrees

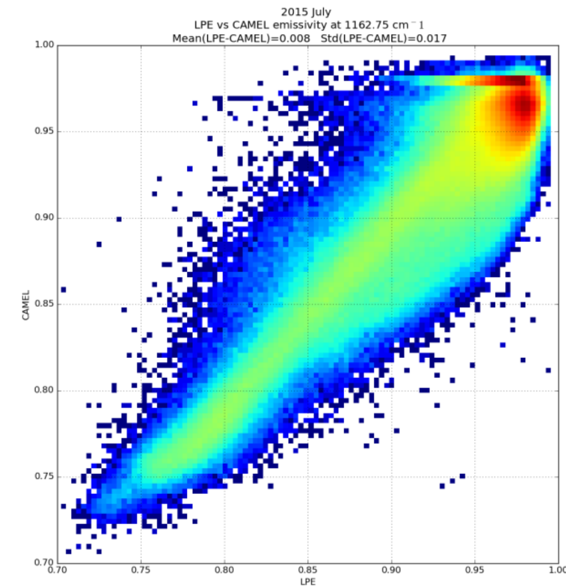

2015 July
LPE vs CAMEL emissivity at 699.25 cm^{-1}
Mean(LPE-CAMEL)=-0.004 Std(LPE-CAMEL)=0.009
CAMEL
LPE


2015 July
LPE vs CAMEL emissivity at 826.5 cm^{-1}
Mean(LPE-CAMEL)=0.002 Std(LPE-CAMEL)=0.009
CAMEL
LPE


2015 July
LPE vs CAMEL emissivity at 885.0 cm^{-1}
Mean(LPE-CAMEL)=0.001 Std(LPE-CAMEL)=0.009
CAMEL
LPE


2015 July
LPE vs CAMEL emissivity at 926.0 cm^{-1}
Mean(LPE-CAMEL)=0.003 Std(LPE-CAMEL)=0.009
CAMEL
LPE


2015 July
LPE vs CAMEL emissivity at 1099.0 cm^{-1}
Mean(LPE-CAMEL)=0.004 Std(LPE-CAMEL)=0.02
CAMEL
LPE


2015 July
LPE vs CAMEL emissivity at 1162.75 cm^{-1}
Mean(LPE-CAMEL)=0.008 Std(LPE-CAMEL)=0.017
CAMEL
LPE

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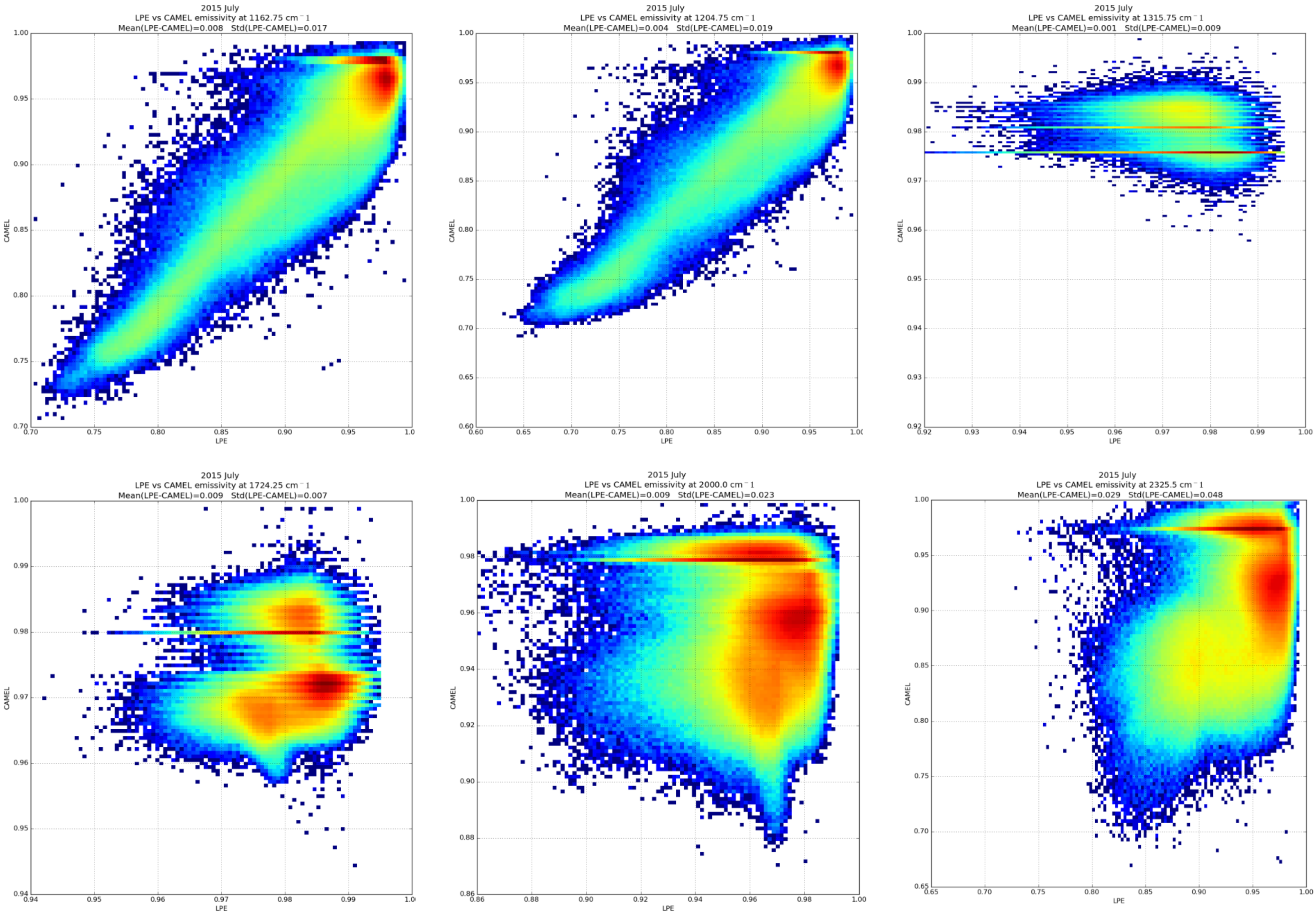
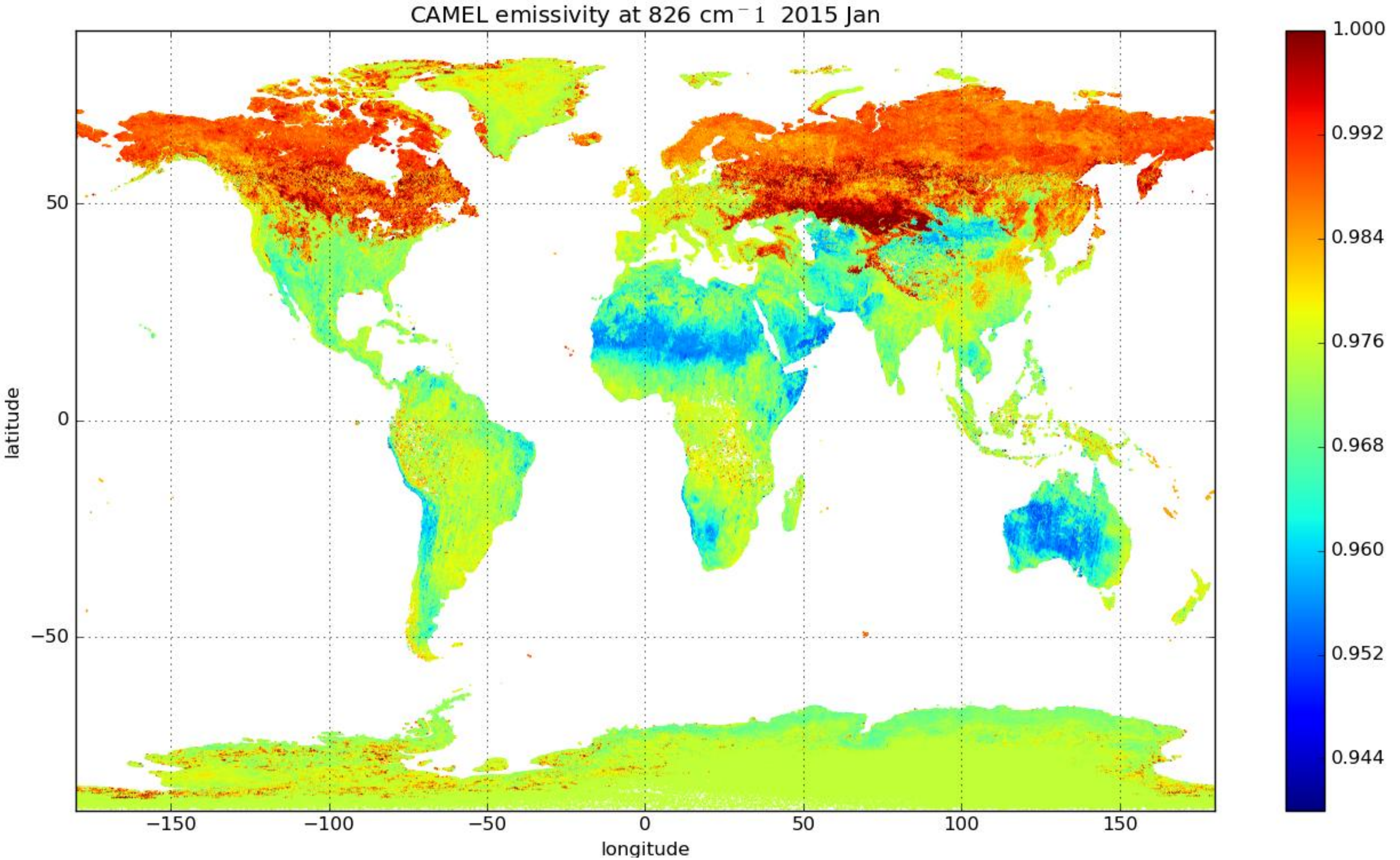
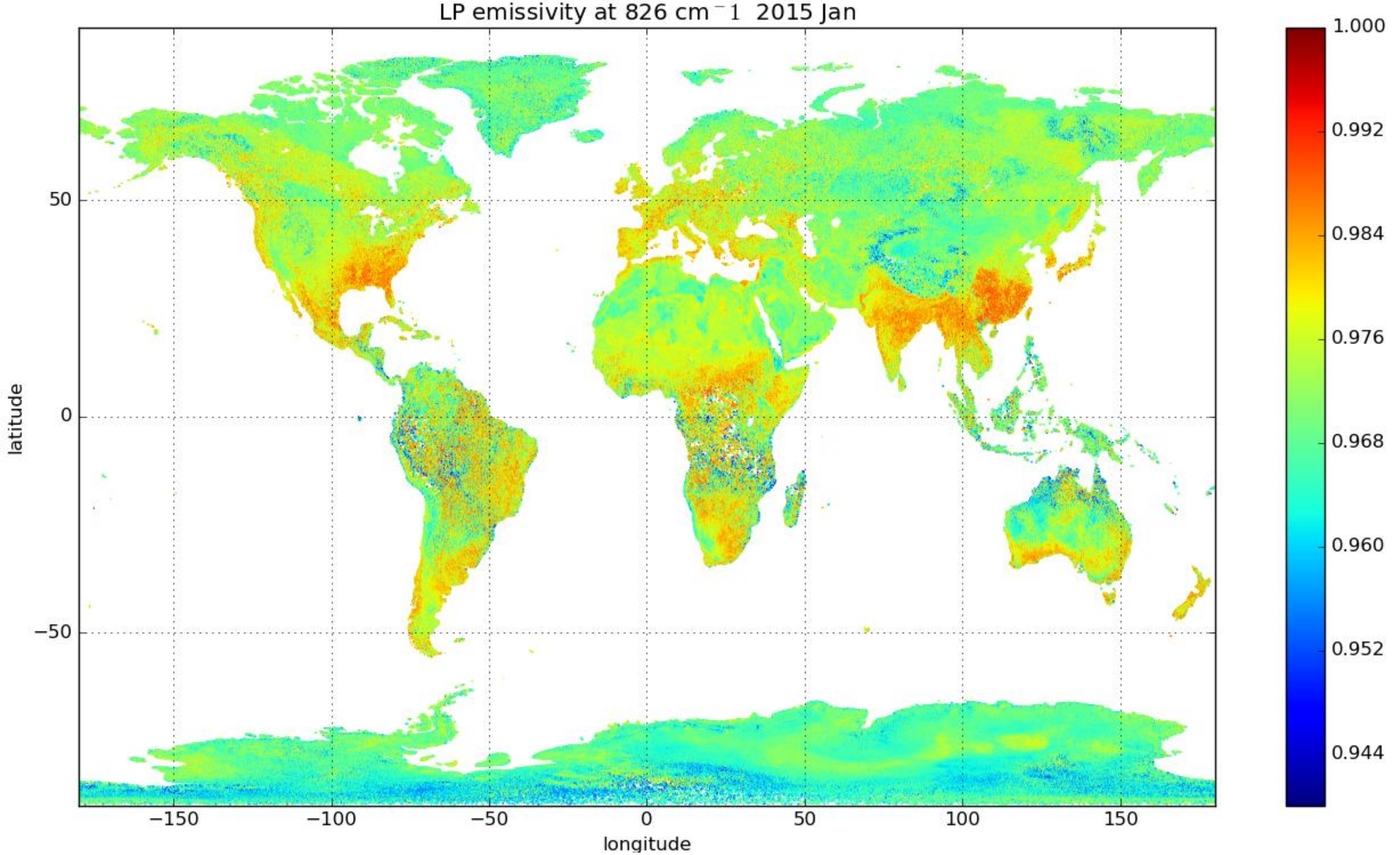
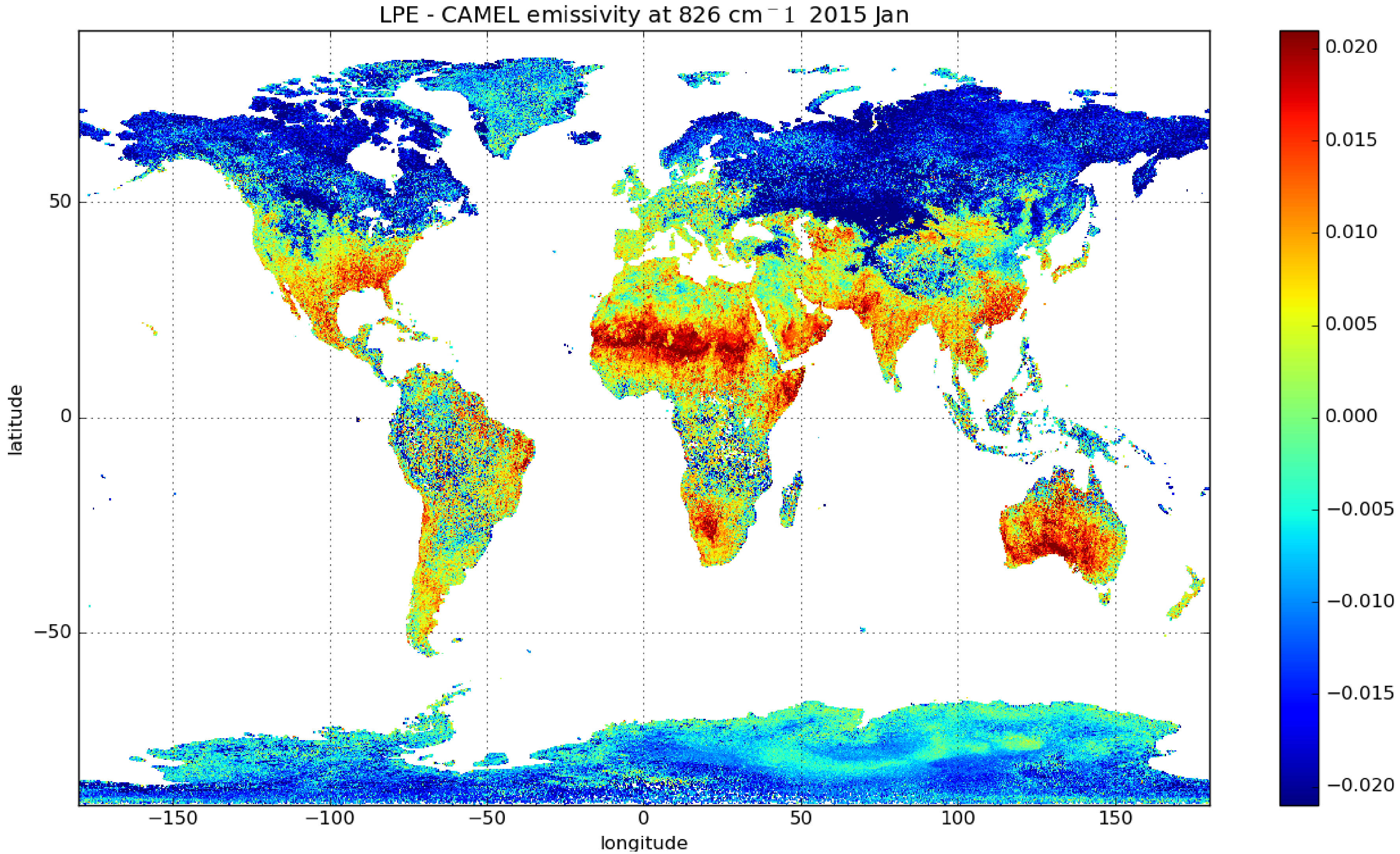

2015 July
LPE vs CAMEL emissivity at 1162.75 cm⁻1
Mean(LPE-CAMEL)=0.008 Std(LPE-CAMEL)=0.017
CAMEL
LPE
2015 July
LPE vs CAMEL emissivity at 1204.75 cm⁻1
Mean(LPE-CAMEL)=0.004 Std(LPE-CAMEL)=0.019
CAMEL
LPE
2015 July
LPE vs CAMEL emissivity at 1315.75 cm⁻1
Mean(LPE-CAMEL)=0.001 Std(LPE-CAMEL)=0.009
CAMEL
LPE
2015 July
LPE vs CAMEL emissivity at 1724.25 cm⁻1
Mean(LPE-CAMEL)=0.009 Std(LPE-CAMEL)=0.007
CAMEL
LPE
2015 July
LPE vs CAMEL emissivity at 2000.0 cm⁻1
Mean(LPE-CAMEL)=0.009 Std(LPE-CAMEL)=0.023
CAMEL
LPE
2015 July
LPE vs CAMEL emissivity at 2325.5 cm⁻1
Mean(LPE-CAMEL)=0.029 Std(LPE-CAMEL)=0.048
CAMEL
LPE


CAMEL emissivity at 826 cm⁻1 2015 Jan
latitude
longitude
50
0
−50
−150
−100
−50
0
50
100
150
1.000
0.992
0.984
0.976
0.968
0.960
0.952
0.944



LP emissivity at 826 cm⁻1 2015 Jan
latitude
longitude
50
0
−50
−150
−100
−50
0
50
100
150
1.000
0.992
0.984
0.976
0.968
0.960
0.952
0.944


LPE - CAMEL emissivity at 826 cm⁻1 2015 Jan
latitude
longitude
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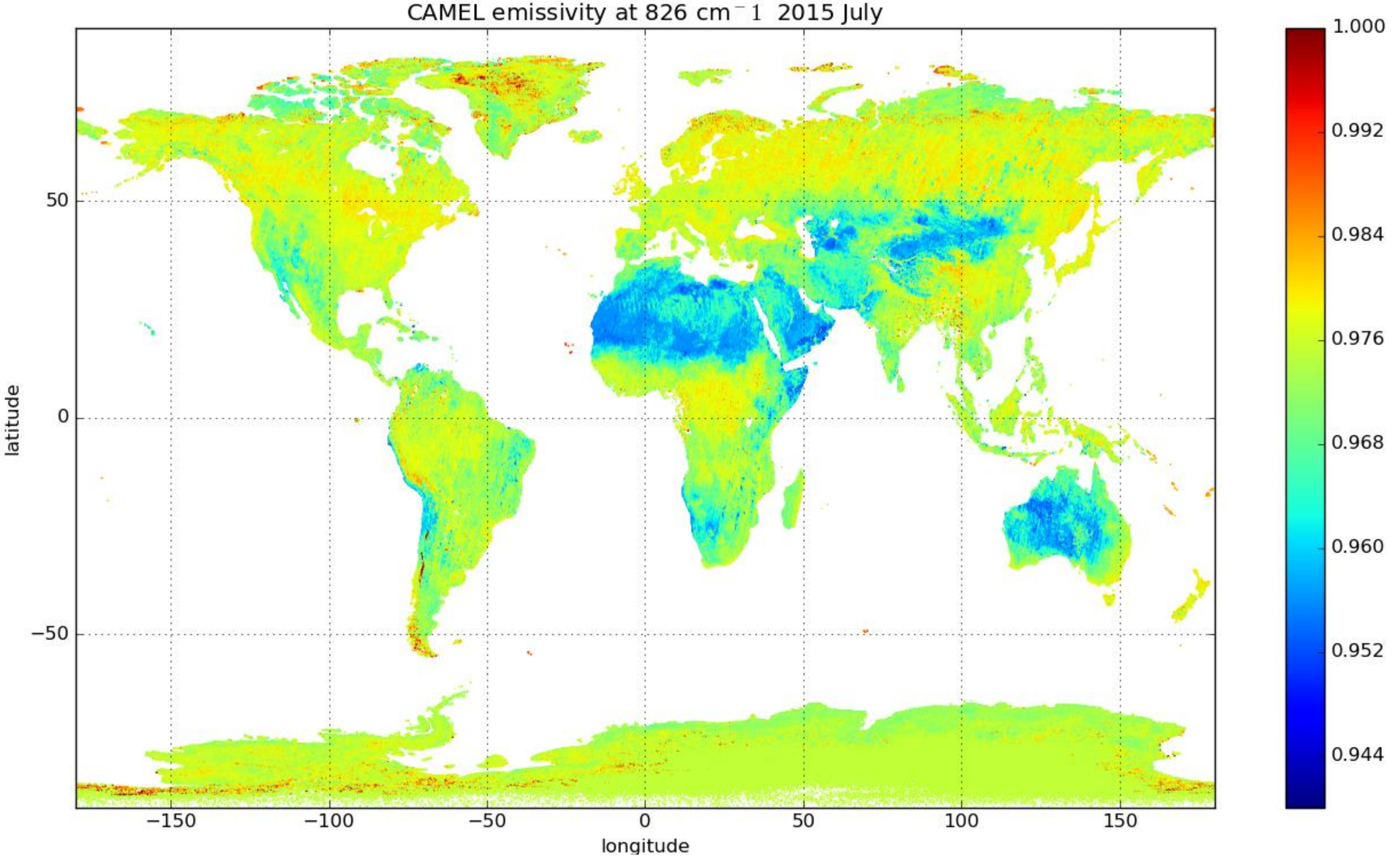
0
−50
−150
−100
−50
0
50
100
150
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
−0.020


CAMEL emissivity at 826 cm⁻1 2015 July
latitude
longitude
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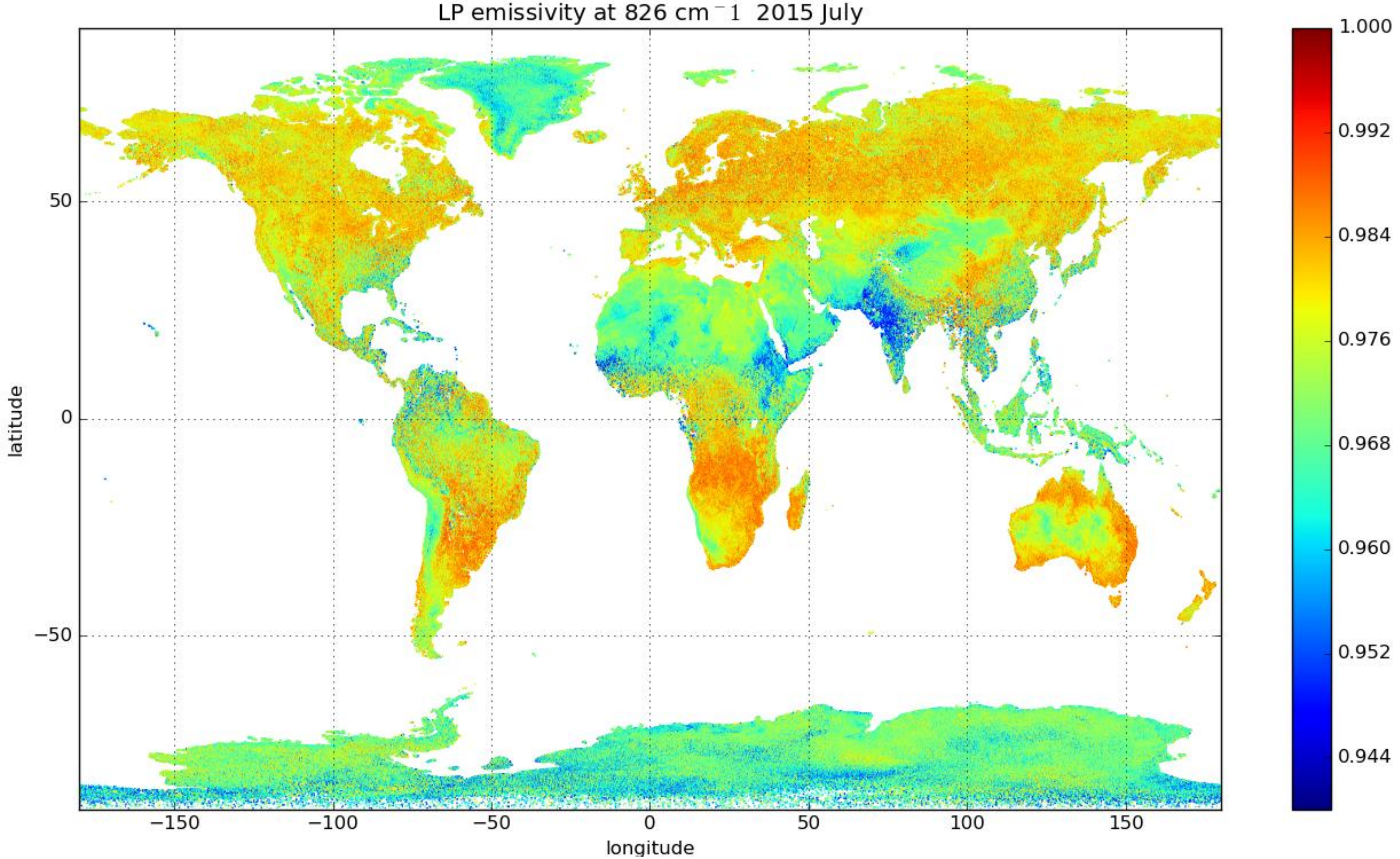
0
−50
−150
−100
−50
0
50
100
150
1.000
0.992
0.984
0.976
0.968
0.960
0.952
0.944



LP emissivity at 826 cm⁻1 2015 July
latitude
longitude
50
0
−50
−150
−100
−50
0
50
100
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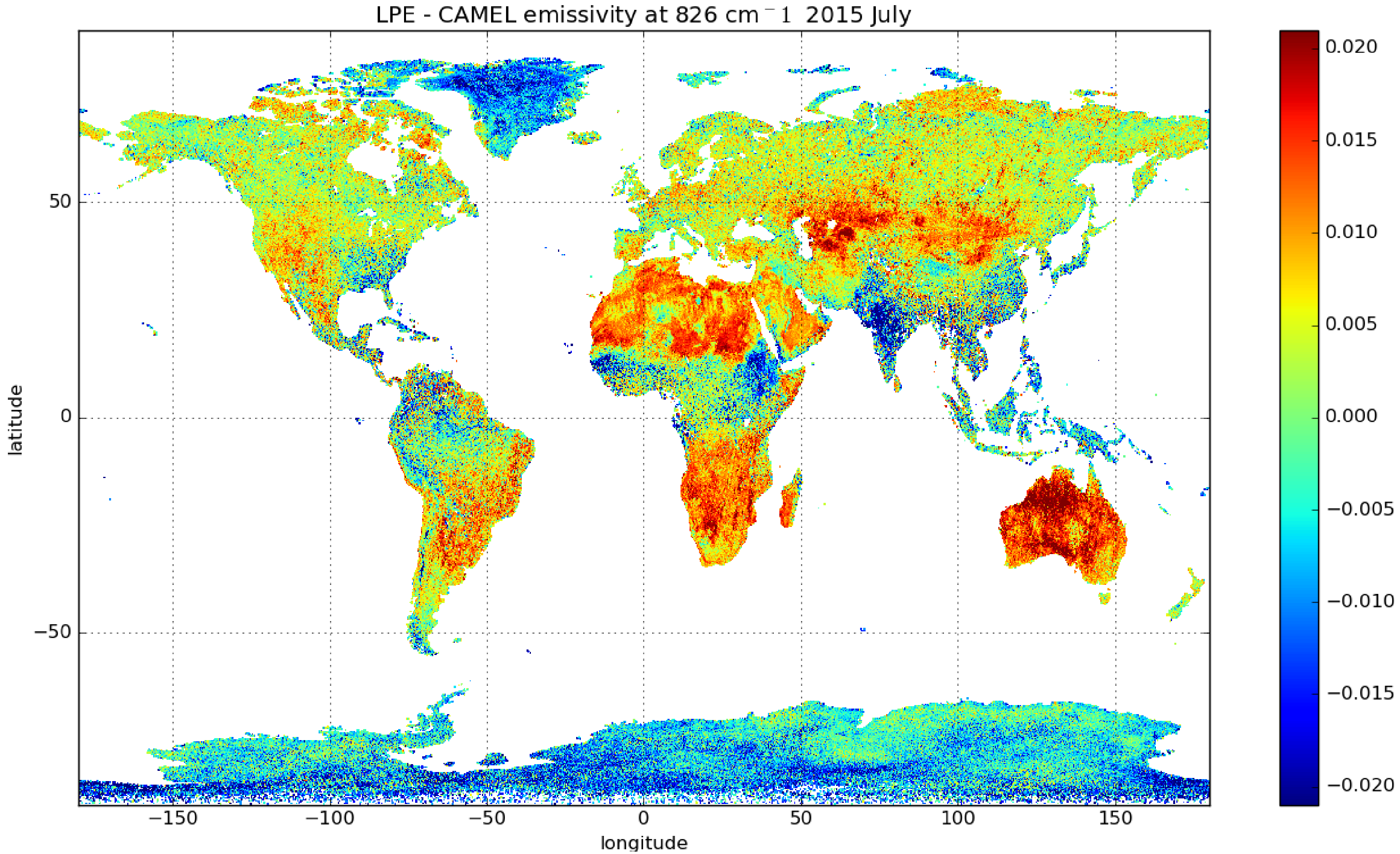
1.000
0.992
0.984
0.976
0.968
0.960
0.952
0.944


LPE - CAMEL emissivity at 826 cm ⁻1 2015 July
latitude
longitude
50
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−100
−50
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50
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0.020
0.015
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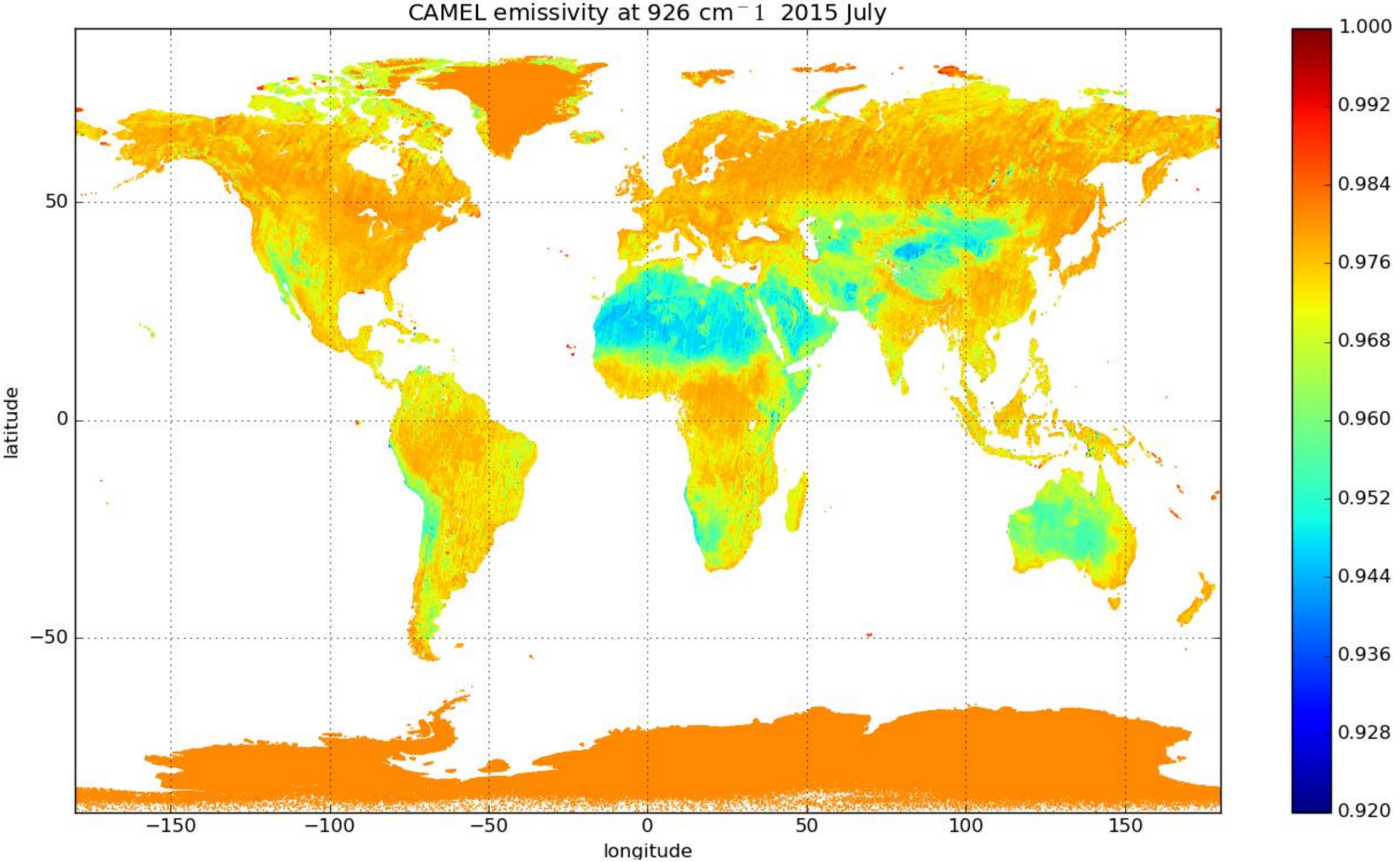
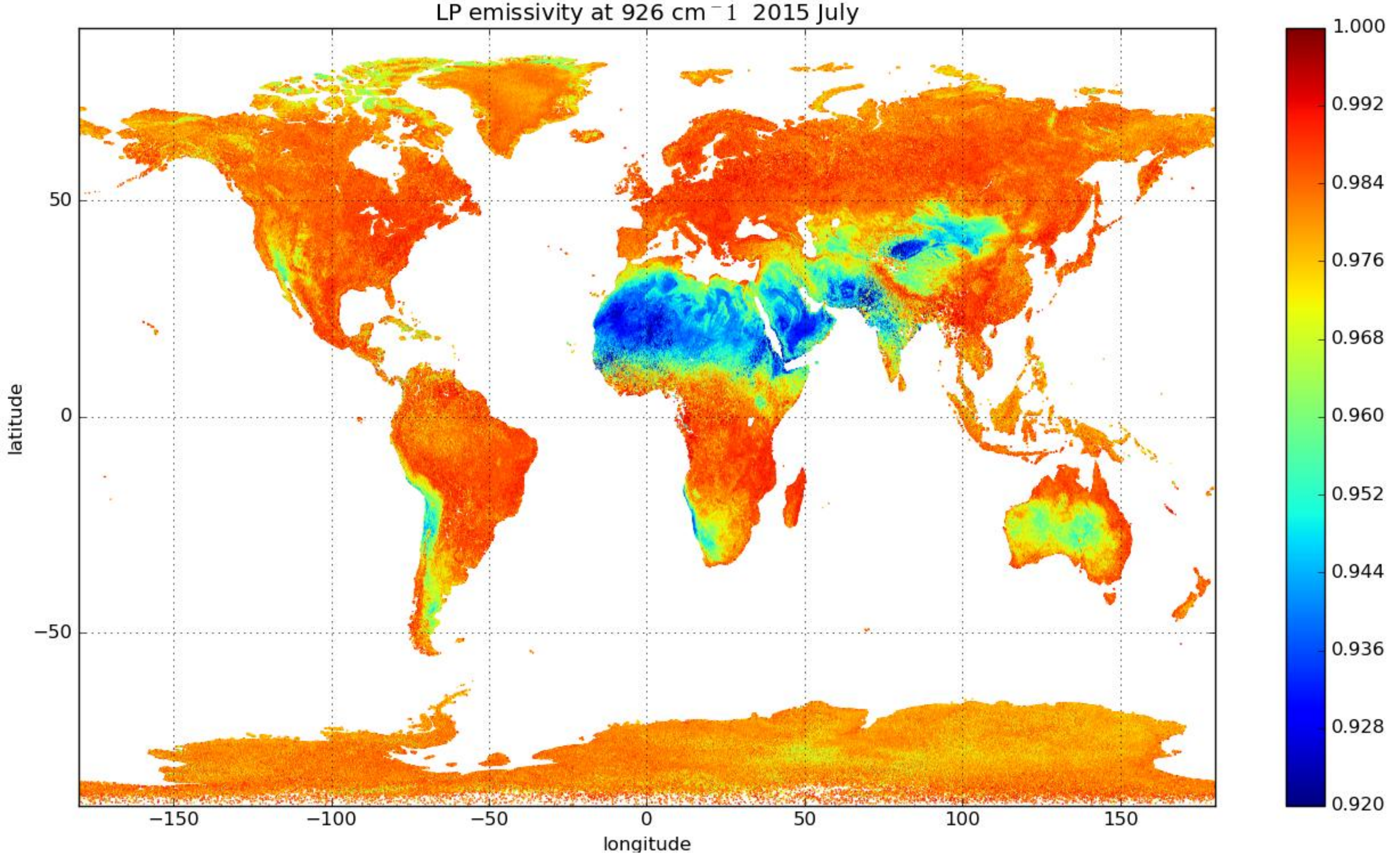
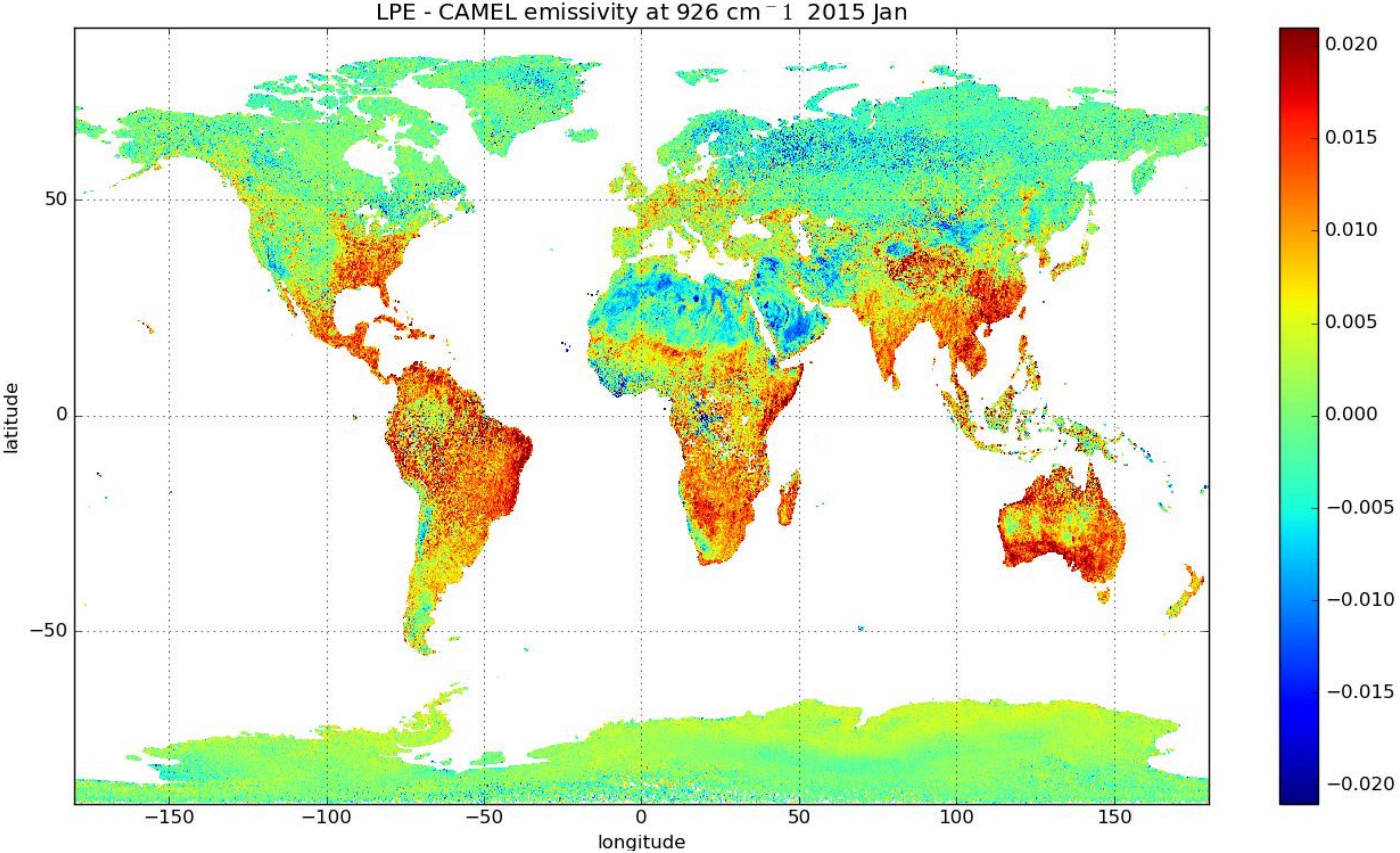
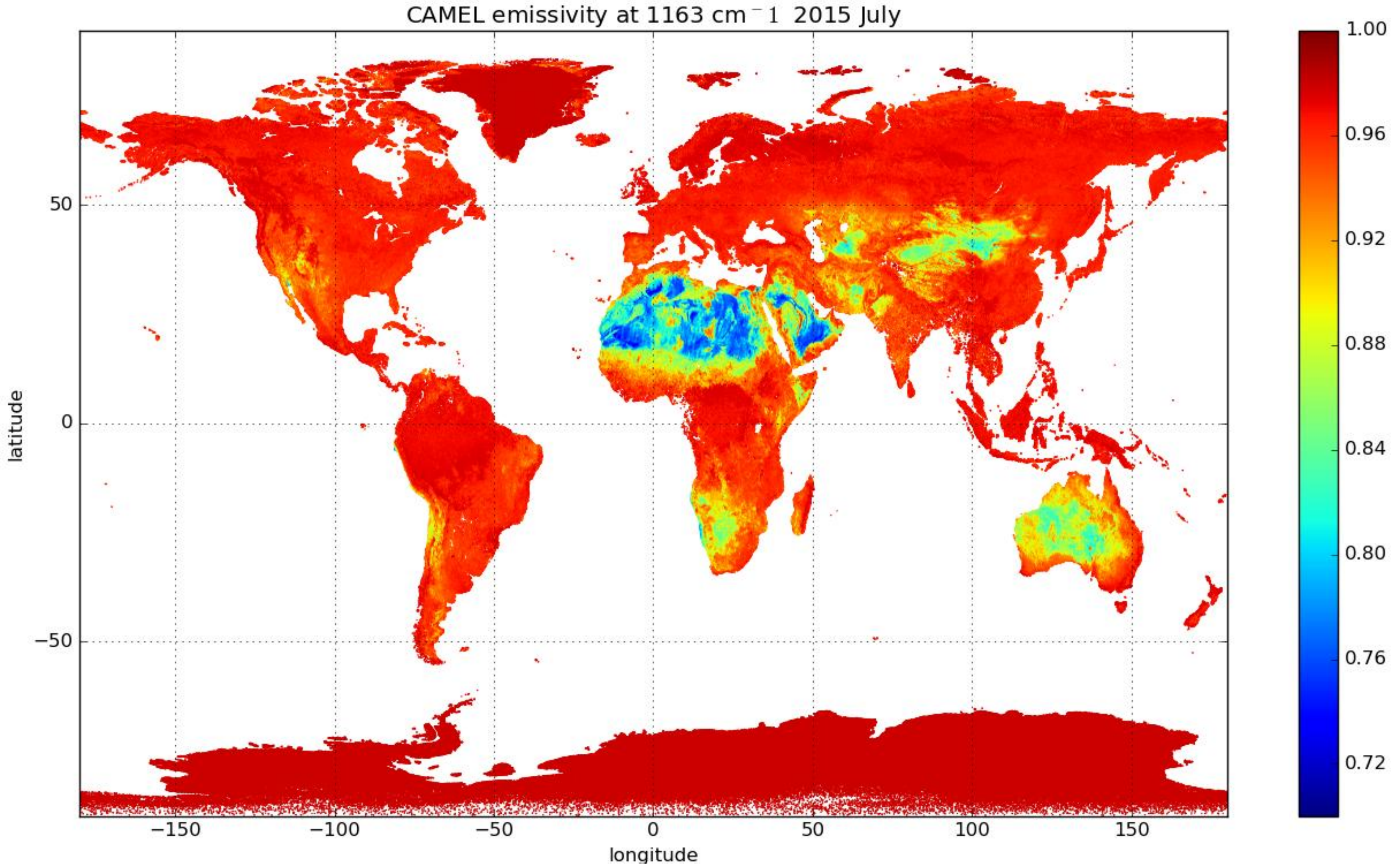
0.005
0.000
−0.005
−0.010
−0.015
−0.020


CAMEL emissivity at 926 cm⁻1 2015 July
latitude
longitude
50
0
−50
−150
−100
−50
0
50
100
150
1.000
0.992
0.984
0.976
0.968
0.960
0.952
0.944
0.936
0.928
0.920

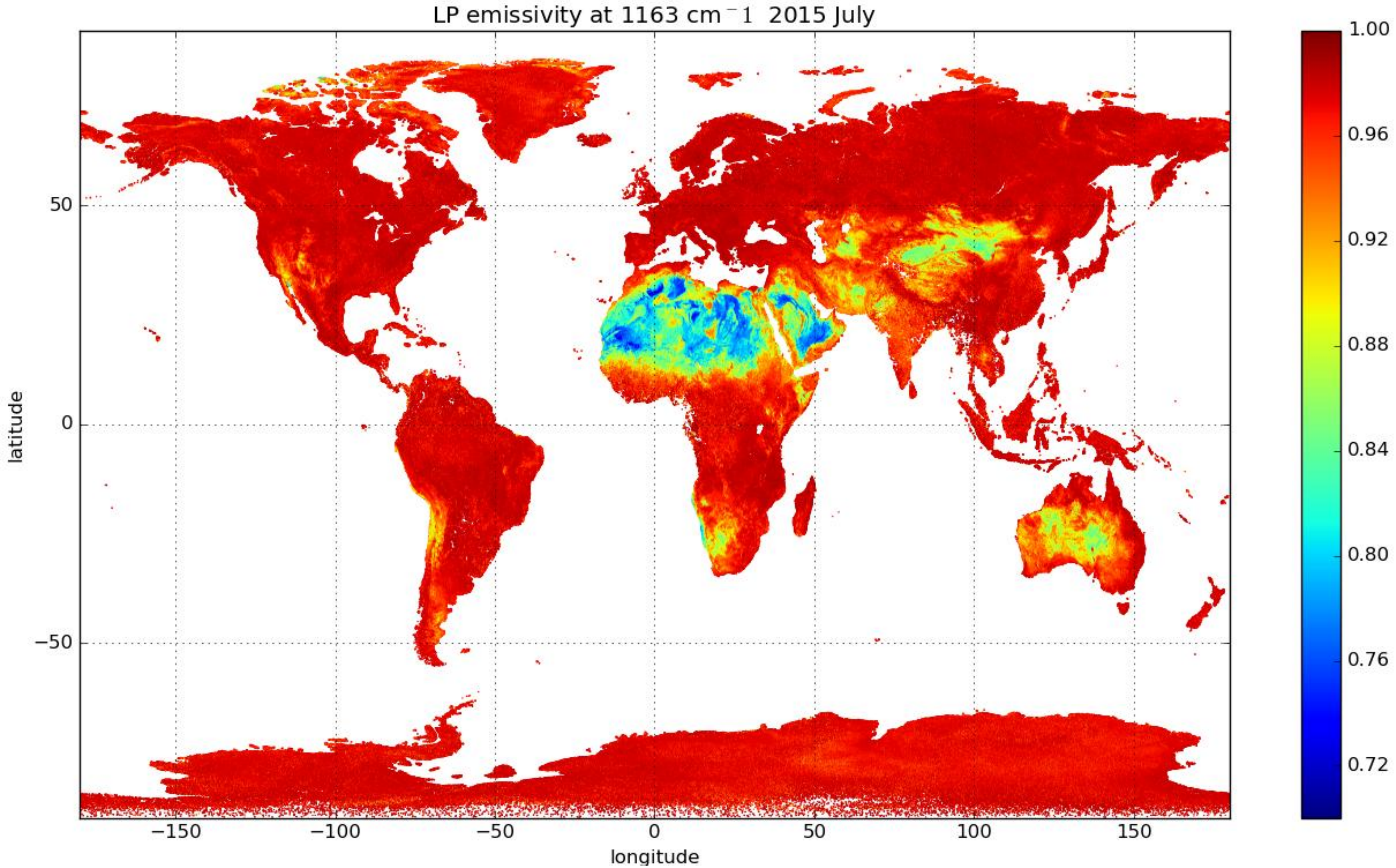

LP emissivity at 926 cm⁻1 2015 July
latitude
longitude
50
0
−50
−150
−100
−50
0
50
100
150
1.000
0.992
0.984
0.976
0.968
0.960
0.952
0.944
0.936
0.928
0.920

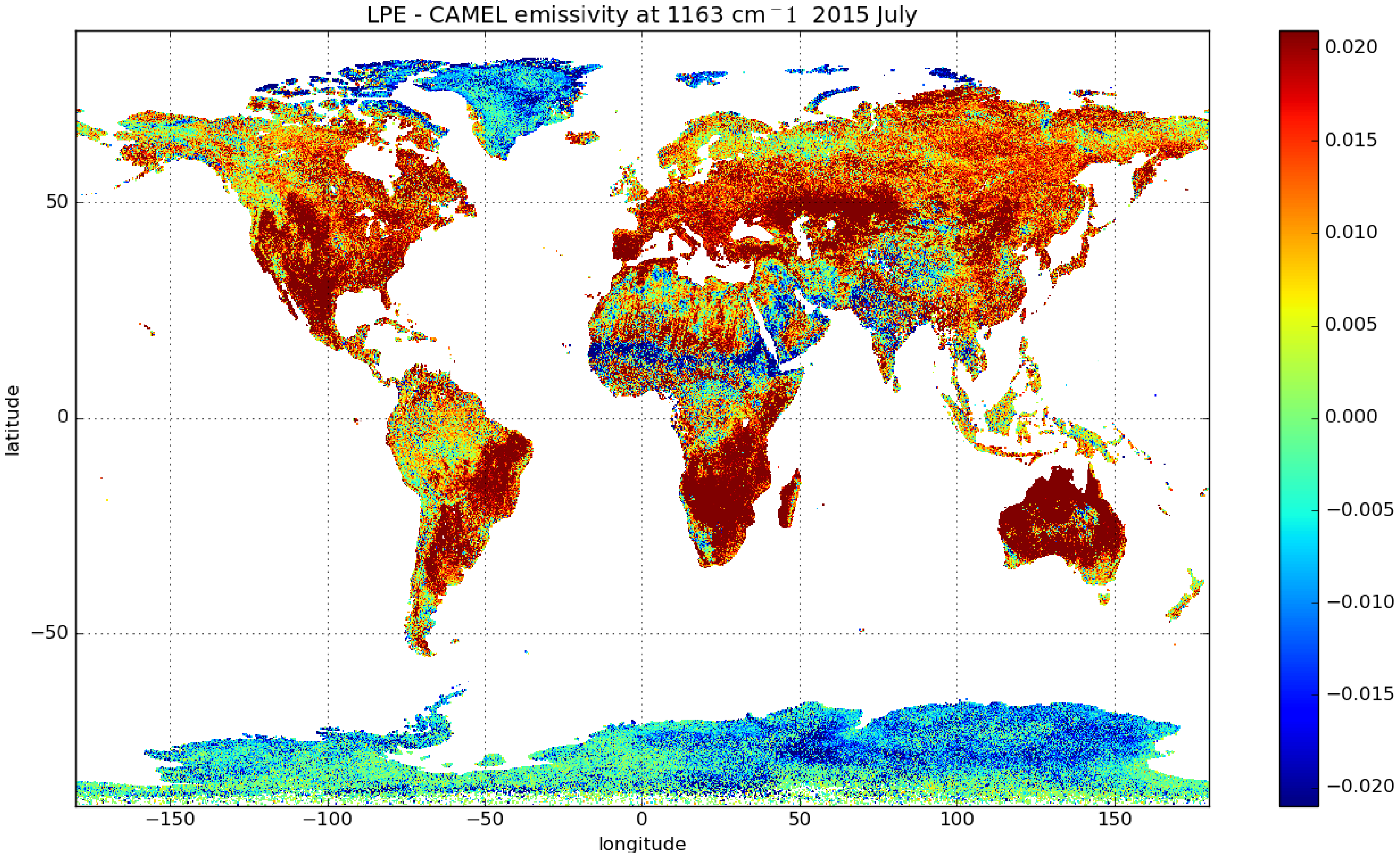


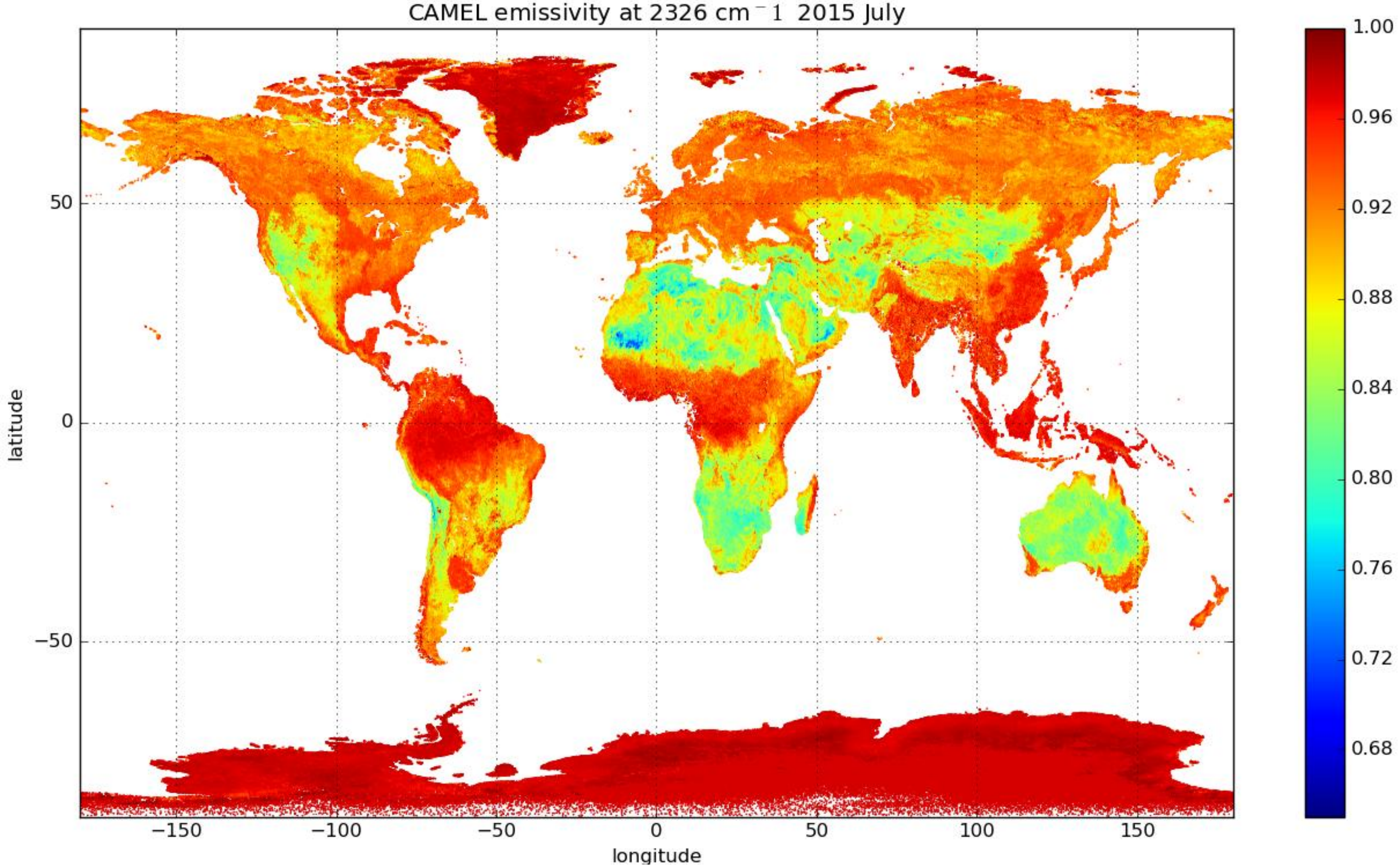
LPE - CAMEL emissivity at 926 cm⁻1 2015 Jan
latitude
longitude
50
0
−50
−150
−100
−50
0
50
100
150
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
−0.020



CAMEL emissivity at 1163 cm⁻1 2015 July
latitude
longitude
50
0
−50
−150
−100
−50
0
50
100
150
1.00
0.96
0.92
0.88
0.84
0.80
0.76
0.72


LP emissivity at 1163 cm^{-1} 2015 July
latitude
longitude
50
0
−50
−150
−100
−50
0
50
100
150
1.00
0.96
0.92
0.88
0.84
0.80
0.76
0.72


LPE - CAMEL emissivity at 1163 cm⁻1 2015 July
latitude
longitude
50
0
−50
−150
−100
−50
0
50
100
150
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
−0.020


CAMEL emissivity at 2326 cm⁻1 2015 July
latitude
longitude
50
0
−50
−150
−100
−50
0
50
100
150
1.00
0.96
0.92
0.88
0.84
0.80
0.76
0.72
0.68

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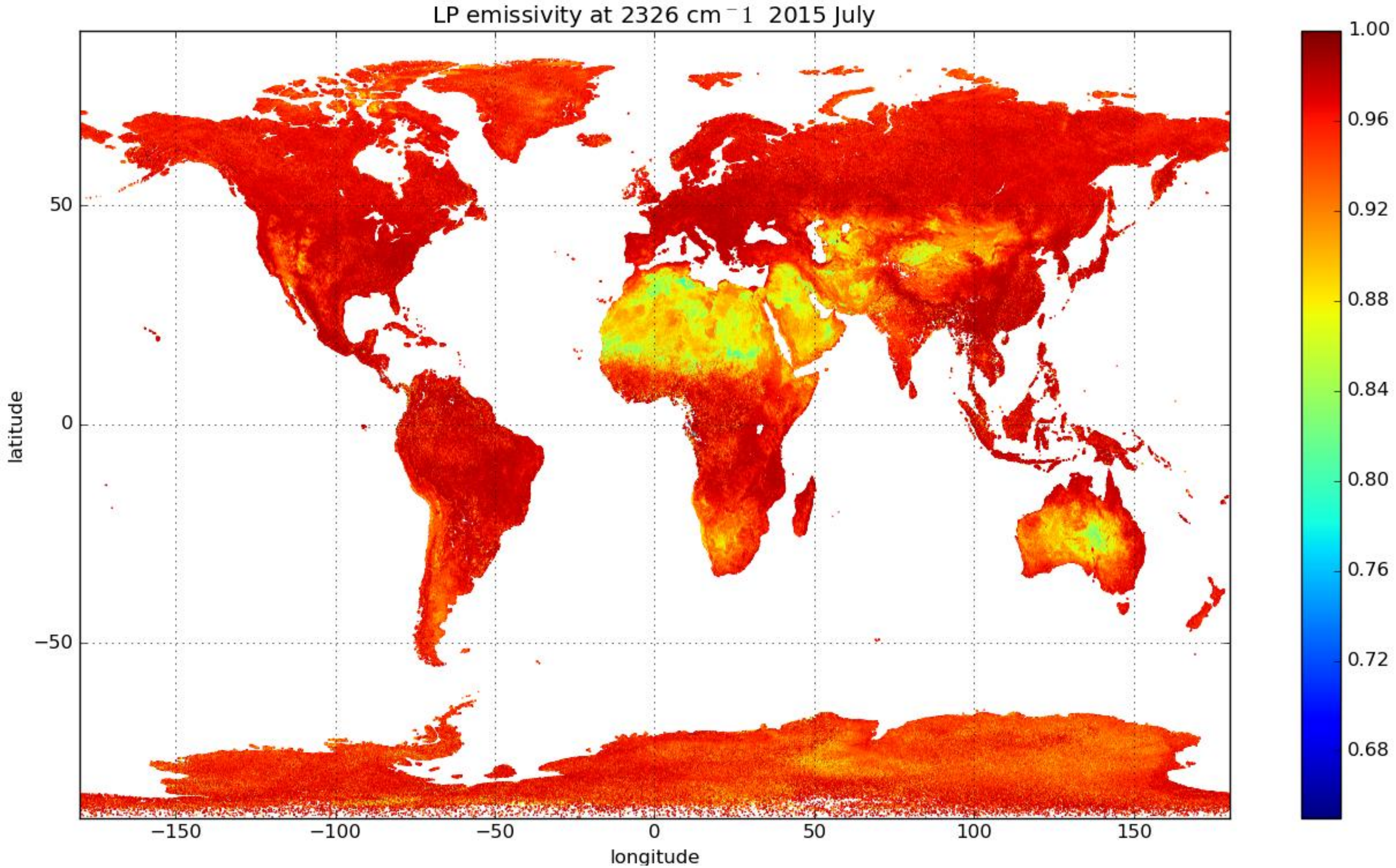
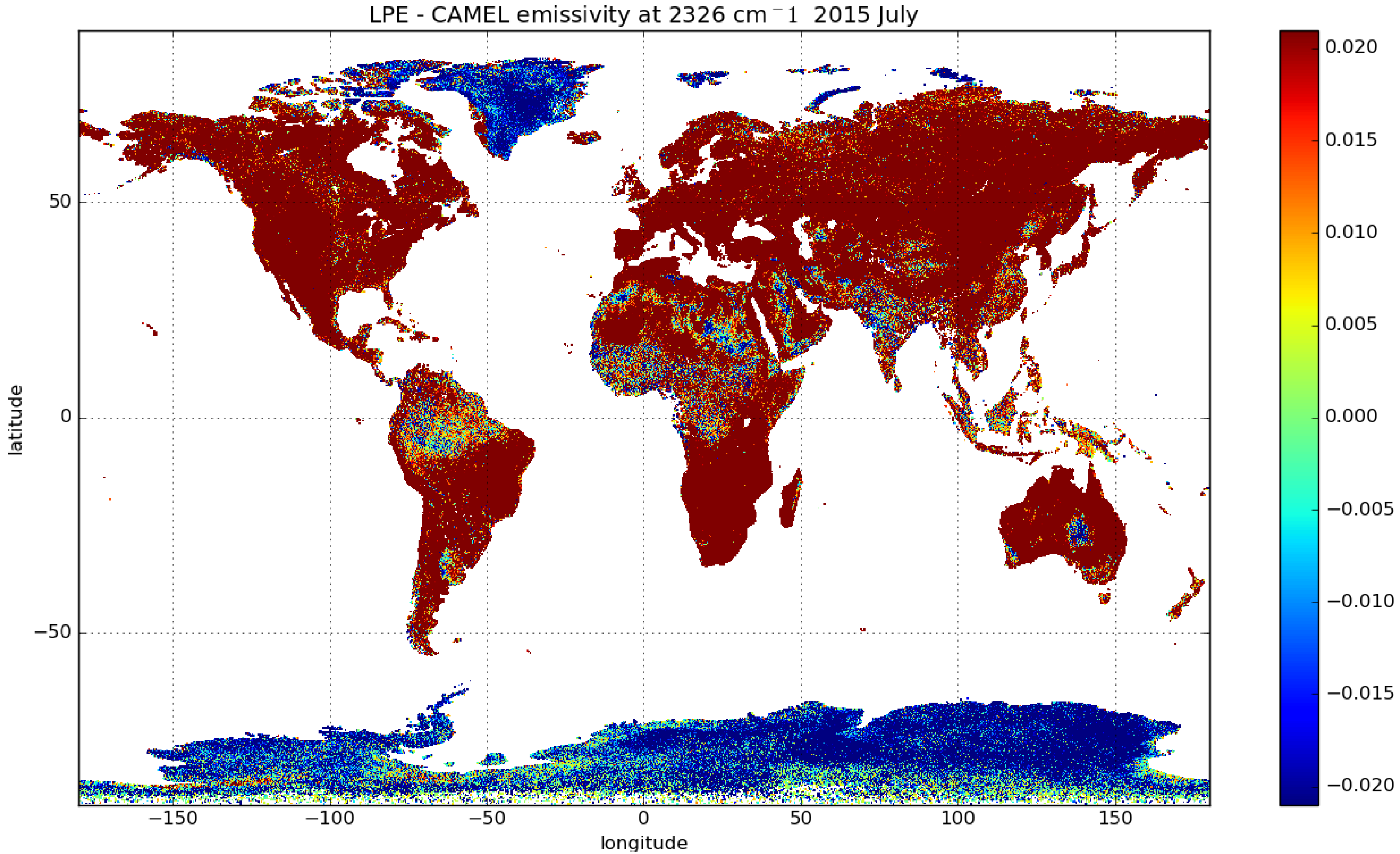
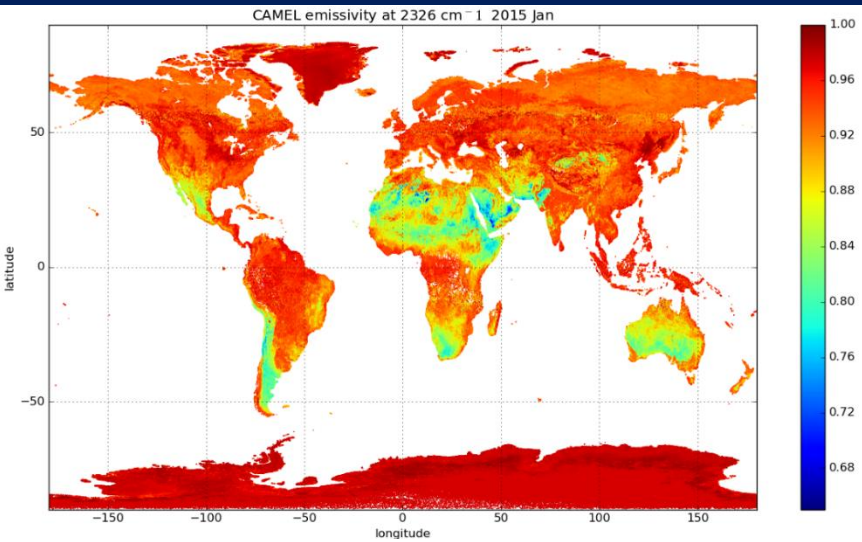
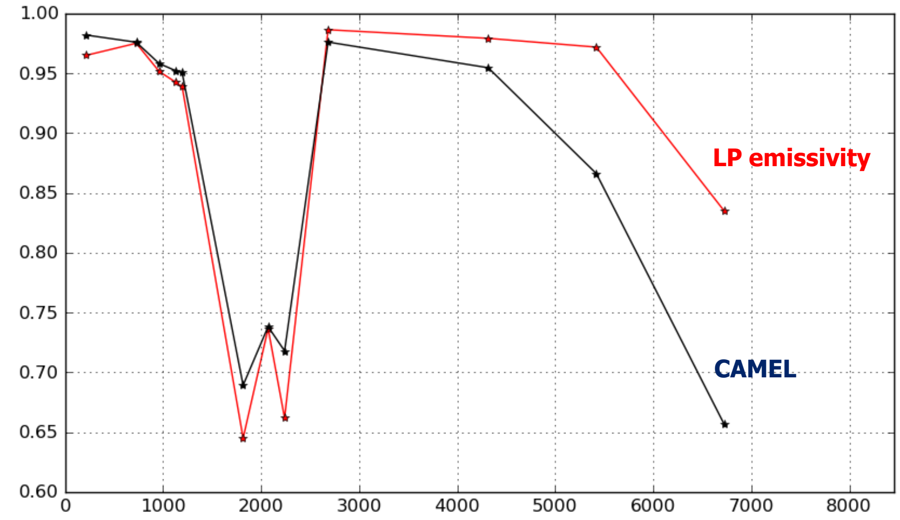
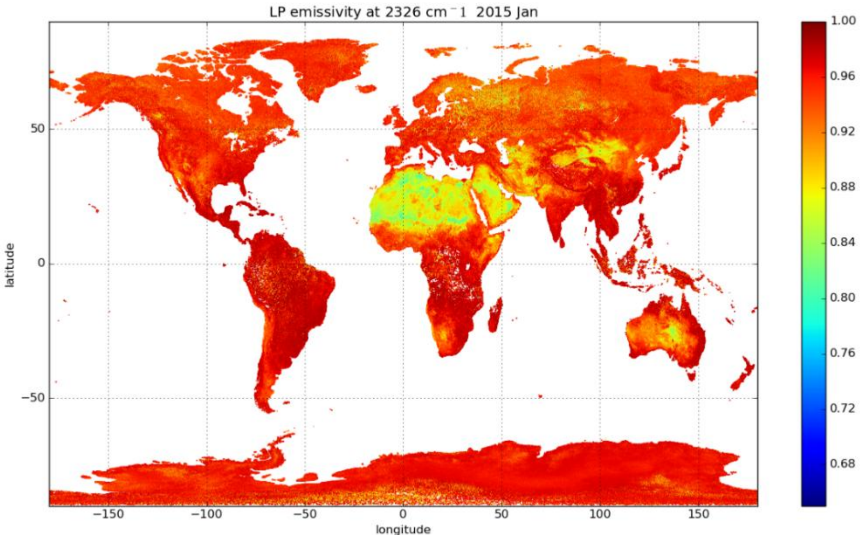

LP emissivity at 2326 cm^{-1} 2015 July
latitude
longitude
50
0
−50
−150
−100
−50
0
50
100
150
1.00
0.96
0.92
0.88
0.84
0.80
0.76
0.72
0.68

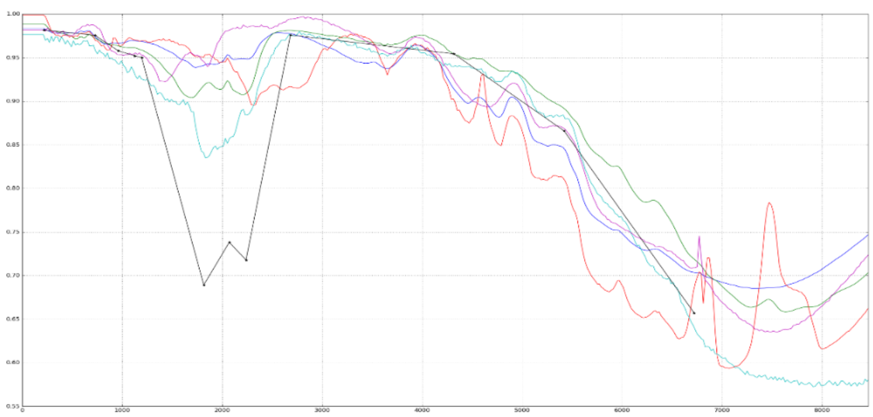

LPE - CAMEL emissivity at 2326 cm⁻1 2015 July
latitude
longitude
50
0
−50
−150
−100
−50
0
50
100
150
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
−0.020

A case January 2015 lon: 12.6-12.8 lat: 25.0-25.2









CAMEL hinge points plotted together with the base spectra for which emissivity at 2326 cm-1 is lowest. CAMEL emissivity cant be represented as a convex combination. The CAMEL HSR effectively must include negative weights.

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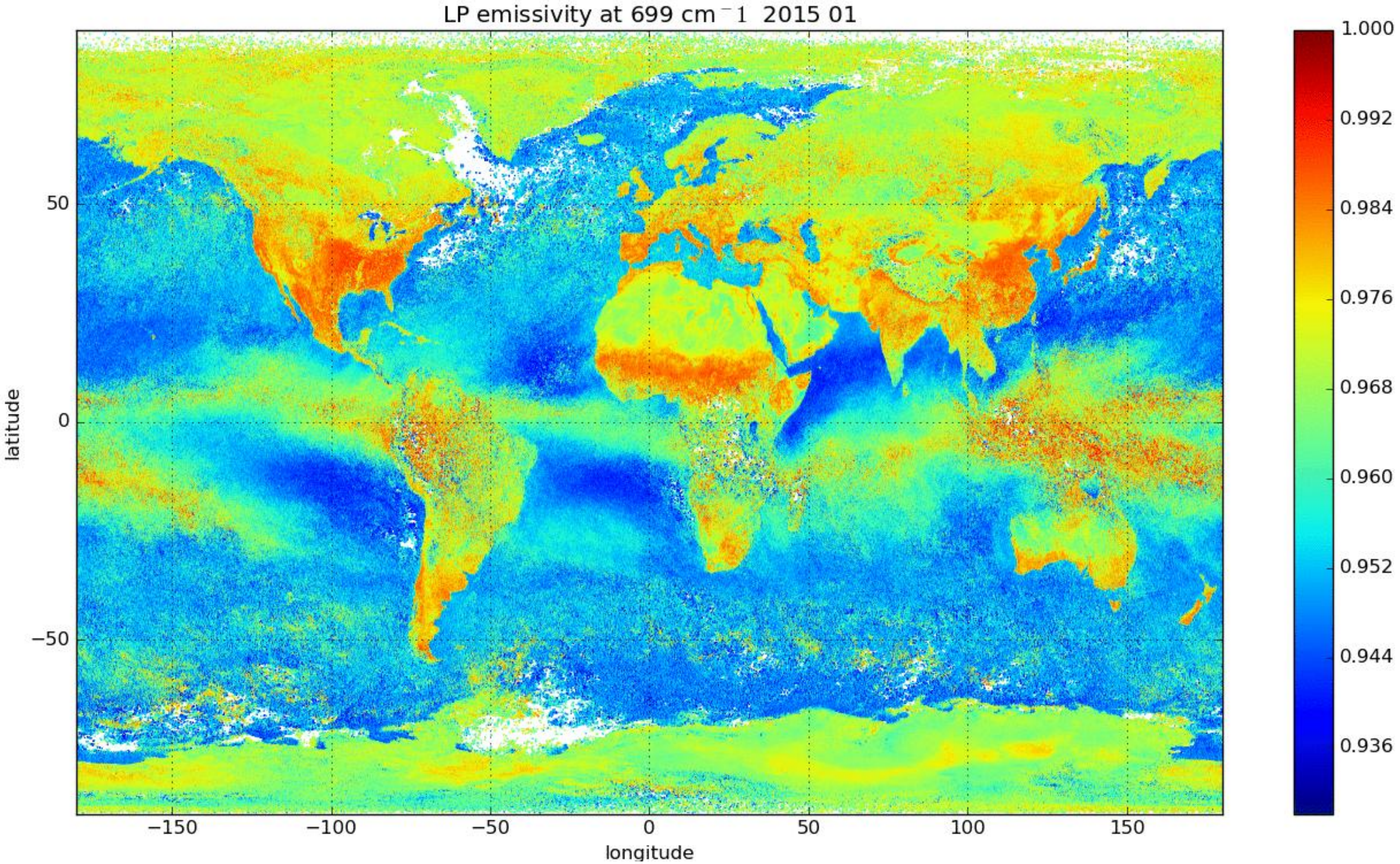
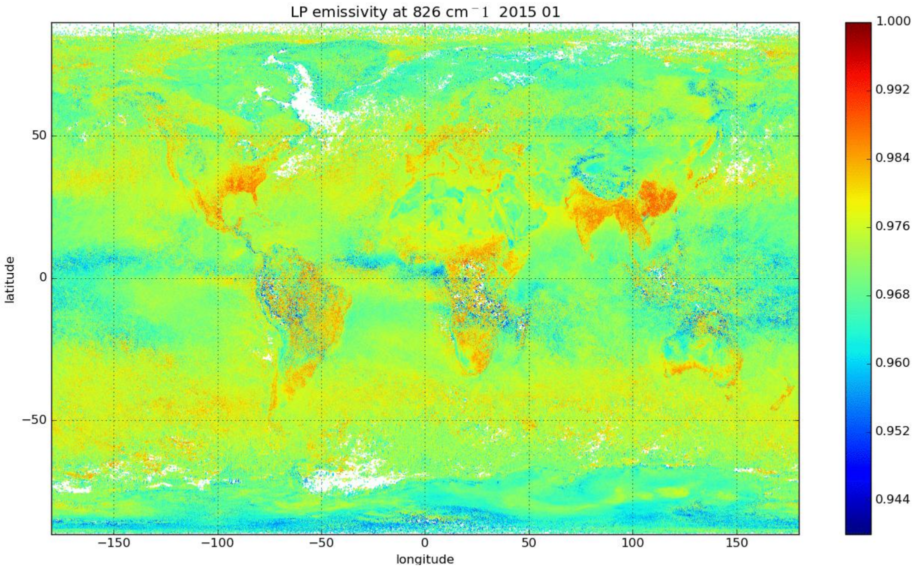
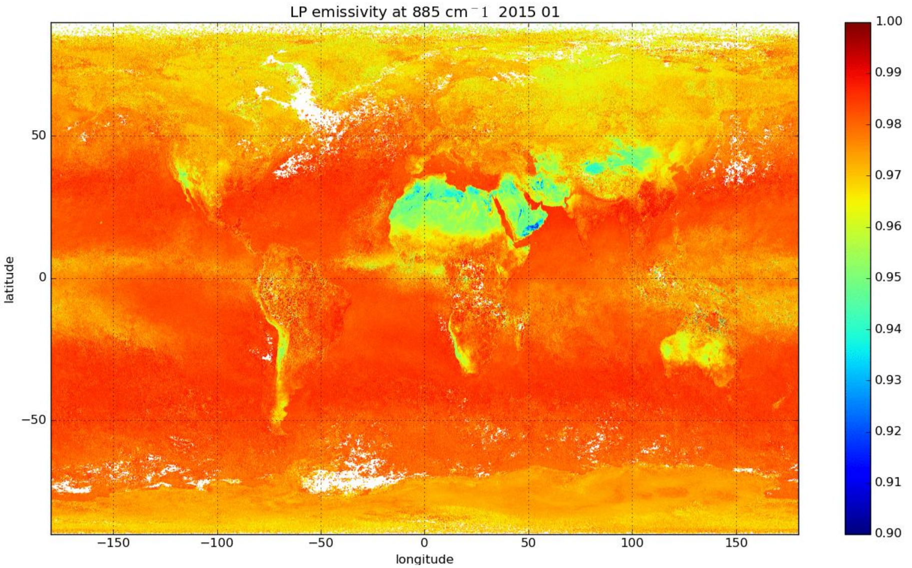
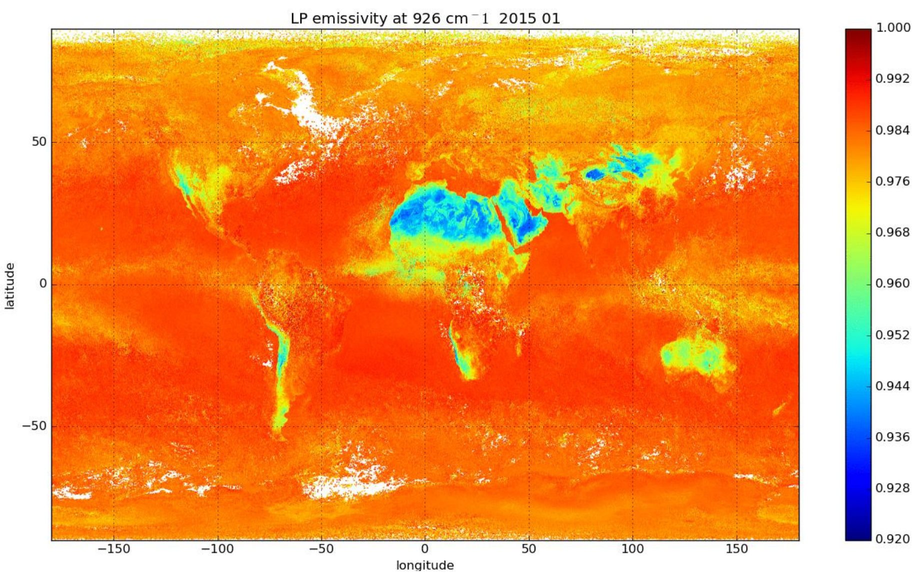
Seasonal variation

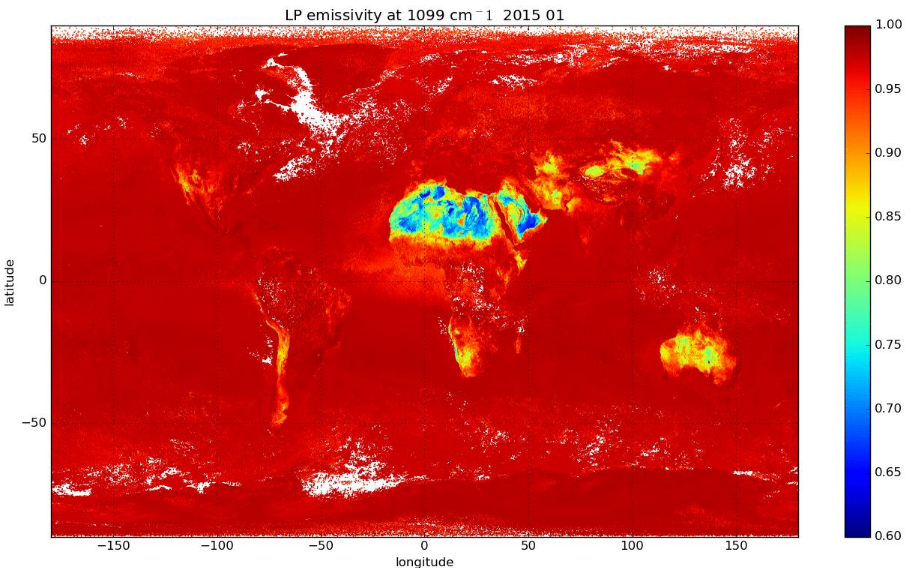


Cloud "contamination", especially in the tropical belt, clearly observed
Snow and sea ice extension variation seems to be well captured


LP emissivity at 826 cm⁻1 2015 01
latitude
longitude
1.000
0.992
0.984
0.976
0.968
0.960
0.952
0.944

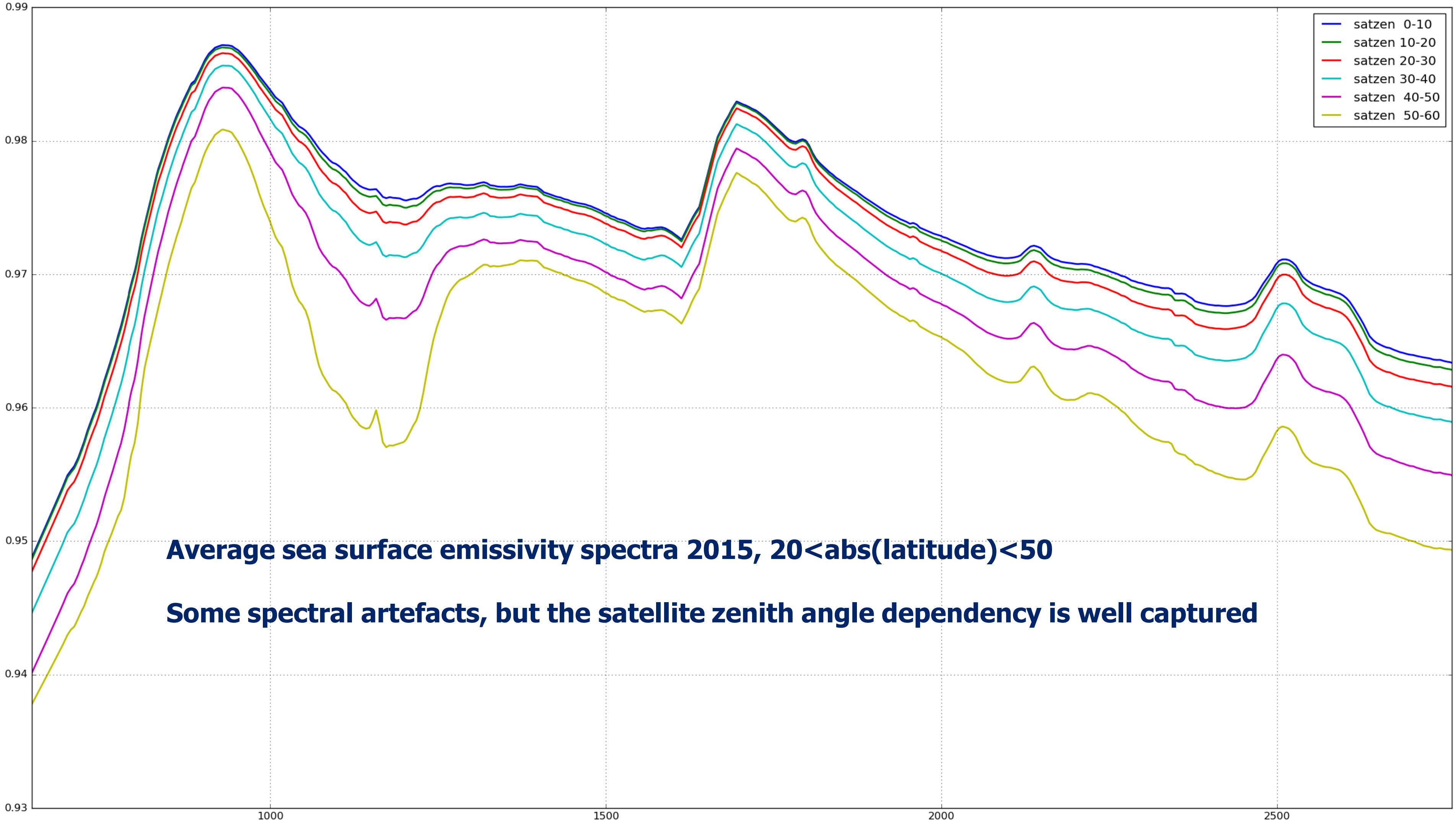

LP emissivity at 885 cm⁻1 2015 01
latitude
longitude
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.90


LP emissivity at 926 cm⁻1 2015 01
latitude
longitude
1.000
0.992
0.984
0.976
0.968
0.960
0.952
0.944
0.936
0.928
0.920


LP emissivity at 1099 cm⁻1 2015 01
latitude
longitude
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60

EUMETSAT

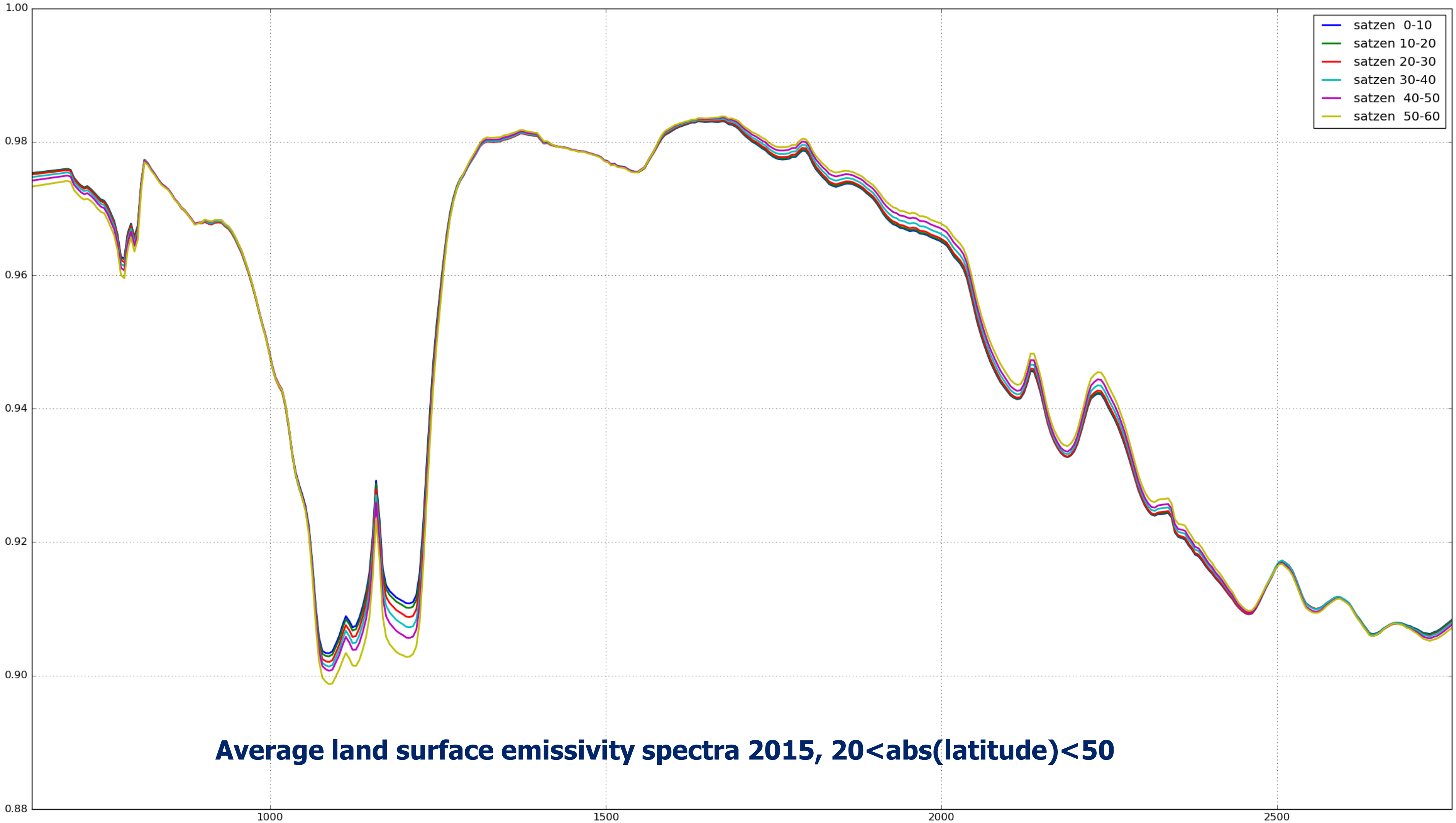
Sea surface emissivity satellite zenith angle dependence



Average sea surface emissivity spectra 2015, 20<abs(latitude)<50

Some spectral artefacts, but the satellite zenith angle dependency is well captured

Land surface emissivity satellite zenith angle dependence



Conclusions / outlook

Surface emissivity is a **very special** parameter to retrieve:
- ❑ high need of regularization
- ❑ a representation as a convex combination of base spectra provides a unique opportunity to regularize the retrieval

Linear programming approach with representation of emissivity as convex combinations of base spectra is feasible.

Results look promising, but deficiencies due to cloud and aerosol contamination are noted:
- ❑ include low cloud and aerosol in the LP retrieval
- ❑ use PC techniques to filter out instrument artefacts from radiances
- ❑ understand differences wrt CAMEL

Further improvements and validation needed before it can replace CAMEL as training target.