Information content of infrared hyperspectral data: clear-sky vs. all-sky

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Outlines

• Motivation
  – Limitation of Polar Orbit sampling
  – Opportunity of GEO/HEO: high-temporal coverage hyperspectral data

• Information content assessments
  – Amplitude of variability: e.g., variance
    Standard deviation (STD=VAR^0.5)
  – Modes of variability: *Counting the infrared (invisible) “colors”*
    Spectral Empirical Orthogonal Function (EOF)
    Degree of Freedom for Signal (DFS)
Absorptive gases & OLR spectrum

- Covering substantial fraction of IR spectrum
- At <1 cm\(^{-1}\) resolution
- High radiometric accuracy

[Goody & Haskins 1998]
Orbits - sampling

- Limited temporal coverage
  - Sun-synchronous: 2 fixed solar times
  - Can’t stare at region of interest
Thinning at 150x150 km² requires ~544,000 hourly sampled profiles to cover the globe.

<table>
<thead>
<tr>
<th>AIRS observations assimilated</th>
<th>November 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average number of profiles after thinning in 24-hour periods = 26854</td>
<td></td>
</tr>
</tbody>
</table>

Perfect coverage: ~700 profiles in every 10x10 deg² box

Note: True coverage is higher, but there are rejections due to clouds.
- GEO and HEO orbits provide opportunities for continuous monitoring of regions of interest

Polar Communications&Weather (PCW) (Canada)

GOES-R (USA)

Fengyun-4 (China)

Highly Elliptical Orbit

Geostationary Orbit

Polar Orbit
Synthetic radiance data

• Atmosphere
  – GFDL GCM: nlayer=24; nlat=90, nlon=124 (~200km resolution) [Huang et al. 2007]
  – Global Environmental Multiscale Model (GEM) of Environment Canada: nlayer=80; nlat=800, nlon=1025 (~30 km resolution) [Garand et al. 2011]
  – Variables: T, q, C

• Radiative transfer model [Huang 2013]
  – Gases: Moderate Resolution Atmospheric Transmission Model (MODTRAN)
  – Clouds: randomly overlapping; parameterized spectral optical properties

• Cases of study
  – GCM: multi-year climatology
  – GEM: weather of 10 days’ (Jan 1-10, 2013) hourly data
Quantifying spectral variability

• Variance
  – STD of radiance of each channel: “Amplitude”

• Spectral EOF
  – Independent piece of information: “Modes”
$dt = 12, t_0 = 6$
$dt = 12, t_0 = 6$

Variability well captured: $\text{std}(t_1) \approx \text{std}(t_2)$
$dt = 12, t_0 = 2$
dt = 12, t0 = 2

Variability not fully captured: std(t1) > std(t2)
dt = 1, full sampling (truth)

- Clear-sky radiance @ 979 cm\(^{-1}\) (atmos. window)
- Reduced sampling rate => Less variability sampled
- Optimal sampling time depends on location

Reduced sampling dt = 12
12 am/pm

6 am/pm

Unit: K\(^2\)

Unit: fraction(sampled/truth-1)
Quantifying spectral variability

• Variance
  – STD of radiance of each channel: “Amplitude”

• Spectral EOF
  – Independent piece of information: “Modes”
Spectral EOF

- Spectral covariance \([nfreq \times nfreq]\)
  \[
  S = (R - \bar{R})^T (R - \bar{R})
  \]
- Eigenvalue problem
  \[
  SV = \lambda V
  \]
  \(V\) : eigenvector – EOF (a total of \(nfreq\) basic modes, each having a dimension of \([nfreq \times 1]\), that describe spectral variability)
  \(\lambda\) : eigenvalue

* available AIRS channels
Analogy: counting the colors

How many colors in a picture?
Infrared (invisible) “colors”

Earth in IR false-colors

How many infrared colors on Earth?
Infrared (invisible) “colors”

Earth in IR false-colors

How many spectral EOFs does the IR world have?
IR spectral fingerprints

Radiance (W/cm²/sr/cm⁳)

Wavelength (µm)

Wave number (cm⁻¹)

CO₂
Ts
Tₚₐₜ
Tₚ₅ₐₜ
Tₛₚ₅ₐₜ
husₚ₅ₐₜ
husₛₚ₅ₐₜ
qₚₐₜ
qₛₚ₅ₐₜ
Cₙₙ
Cₙₙₖ
Cₙₙₕ
Measured/simulated global spectral EOFs ("colors")

Earth in IR false-colors

How to determine the colors?
- spectral EOF

\[ S = (R - \bar{R})^T (R - \bar{R}) \]
\[ SV = \lambda V \]

Model captures the leading EOFs (dominant "colors")
Expansion Coef. (intensity of each color)

EOFs (colors)

Spatial variability of time-mean radiance spectrum disclosed here.
Discrepancy in expansion coef. discloses model biases in atmos. variability simulation:
EOFs of temporal spectral variation at different locations

Continent (mid-lat)  Everest (mount.)  Greenland (ice)  Gobi desert

Temporal variability

Regionally different - reflecting diff. atmos. variability in diff. regions
Measure of spectral variability

1) # of significant EOFs

Procedure: first, determine the EOFs using the covariance of all the spectra (at all locations and at all the times: 1e8 spectra)

\[ S_{\text{global}} = (R - \bar{R})^T (R - \bar{R}) \]

\[ S_{\text{global}} V_{\text{global}} = \lambda_{\text{global}} V_{\text{global}} \]

Then, project local covariance to the EOFs determined above and obtain the corresponding eigen values

\[ \lambda_{\text{local}} = V_{\text{global}}^T S_{\text{local}} V_{\text{global}} \]

Then, apply North’s rule of thumb

2) Degree of Freedom for Signal (DFS) [Rodgers 2000]

\[ \text{trace}(S_a), \text{ where } S_a = (S^{-1} + S_e^{-1})^{-1} S_e^{-1} \]

\[ S_e : \text{obs. error matrix} \]
DFS: number of discernible infrared colors

- The world is more “colorful” with clouds
Sampling impact on DFS: clear-sky

- Reduced sampling rate => reduced amount of information (>10%)
- Optimal sampling time depends on location (season)
Sampling impact on DFS: all-sky

- Generally greater reduction of I.C. in all-sky
- Optimal sampling time depends on location (season)

Unit: # of DFS

Change in DFS
Summary

• Information content (IC) of high-coverage hyperspectral data is quantified by measuring the spectral variability
  – Variance / trace of covariance: amplitude
  – EOF / DFS: independent pieces of IC (modes)

• Polar orbit sampling captures a fraction of the overall variability – potential of GEO/HEO orbits
  – Loss of amplitude
  – Loss of variability modes

• Future work
  – OSSE
Possible impact on forecast

• Serial correlation of forecast error
  – Two forecast sequences
    S1: forecast issued at t0
    S2: forecast issued at t0+6hr – “Obs. Truth”
  – Forecast error dR: R1 – R2
  – Correlation coefficient Corr(dR(t1), dR(t1+dt)) computed for different dt
Serial correlation of forecast error

\[ \text{Corr}(dR(t1), dR(t1+dt)) \]
\[ dR = R_{\text{forecast}} - R_{\text{obs}} \]

Forecast error quickly decorrelated: timely assimilation of radiance data may potentially improve forecast.
Spectrally decomposed sensitivity of clear-sky OLR at each 10 cm⁻¹ interval to 10% perturbation of specific humidity at each 50-mb layer.
[Huang, Ramaswamy and Soden 2007 JGR]

- Window region: most sensitive to lower troposphere (water vapor continuum absorption)
- H2O bands: middle- and upper-troposphere
- Reduced sensitivity in CO2 and O3 bands.
GCM vs. AIRS
Global annual mean spectra

Clear-sky

All-sky

[Huang et al. 2007 GRL]
Model – satellite difference spectrum

All-sky MODEL-AIRS radiance difference

<table>
<thead>
<tr>
<th>Unit: W m⁻²</th>
<th>OLR</th>
<th>Window band</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>All sky</td>
<td>Clear sky</td>
</tr>
<tr>
<td>CERES</td>
<td>241.73</td>
<td>275.87</td>
</tr>
<tr>
<td>GCM</td>
<td>240.63</td>
<td>263.43</td>
</tr>
<tr>
<td>GCM-CERES</td>
<td>-1.10</td>
<td>-12.44</td>
</tr>
</tbody>
</table>

[Huang et al. 2007 GRL]
DFS

- The world is more “colorful” with FIR
(with FIR - without FIR) #DOF
full-sample (t0=1,dt=1), all sky
Impact on forecast

- Serial correlation of forecast error
  - Two forecast sequences
    - S1: forecast issued at t0
    - S2: forecast issued at t0+6hr – “Obs. Truth”
  - Forecast error dR: R1 – R2
  - Correlation coefficient Corr(dR(t1), dR(t1+dt)) computed for different dt
Forecast error quickly decorrelated: timely assimilation of radiance data may potentially improve forecast.

\[ \text{Corr}(\text{dR}(t_1), \text{dR}(t_1+dt)) \]
\[ \text{dR} = R_{\text{forecast}} - R_{\text{obs}} \]

Serial correlation of forecast error
\[ I_v(z) = \int_{0(+\infty)} B_v(T(z'))W(z')dz' \]

where \[ W(z') = \frac{dTr(z';z)}{dz'} \] : "weighting function". \[ Tr(z';z) = e^{-\tau(z) - \tau(z')/\mu} \] : "transmission function"

**W(z):**
- Links \( T(z) \) and \( I_v \)
- Key to deciphering the radiance spectrum