Monitoring Earth’s global energy balance from space
– requirements –

Thorsten Mauritsen, Steven Dewitte, Thomas Hocking, Linda Megner, Luca Schifano
Climate out of balance

- Energy is accumulating because of increasing greenhouse gases

- This causes:
  - Rising temperatures
  - Shifting climate zones
  - Droughts and heat waves
  - Flooding
  - Increasing sea levels

- Yet, imbalance is only 1 out of 340 Wm$^{-2}$, or 0.3 percent
Societal benefits from long term monitoring

Governments of the world have agreed to limit global warming below 2 degrees

- Requires declining imbalance:
  - follow up on international agreement

- Prepare for worst-case scenarios:
  - aerosol forcing larger than expected: rapid warming ahead!
  - global tipping-point, extremely unlikely but catastrophic impact
  - geo-engineering may be needed in future

Simulations of past and future scenarios:
Requirements

To be useful, a system must have drifts and errors that are smaller than the signal we want to measure, preferably much smaller.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>$\ll 0.2 \text{ Wm}^2$/decade</td>
</tr>
<tr>
<td>Systematic error</td>
<td>$&lt; 1.0 \text{ Wm}^2$</td>
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<tr>
<td>Random error</td>
<td>$&lt; 1.0 \text{ Wm}^2$</td>
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Making the problem simpler

- Sacrifice resolution for accuracy
- Focus on global annual mean imbalance
- Maintainable and stable over decades
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• Sacrifice resolution for accuracy
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Past, current and planned missions use scanners

All scanning radiometers depend on angular dependency models (ADMs) to correct for narrow field of view

- ERBE
- CERES
- Libera
- CLARREO-Pathfinder
- ESAs TRUTHS, FORUM, IASI-NG

\[
F(\theta_S) = \frac{\pi I(\theta_S, \theta_V, \phi)}{R(\theta_S, \theta_V, \phi)}
\]

From Gristey et al. (2021)
Anisotropic effects

Wide field of view radiometer measures actual flux at satellite position

However, systematic biases in viewing- and solar zenith angles may introduce biases:

• Gristey et al. (2017) explored effects of anisotropic using TRMM angular dependence model (ADM)
  
• Found difference when introducing ADM of 1.6 Wm$^{-2}$ compared with isotropic case

• But only 0.1 Wm$^{-2}$ between true and randomised ADMs
The Earth Climate Observatory (ECO) mission

- Consist of polar orbiting satellites
- Observe incoming and outgoing radiation with identical instruments
- Rotate to cancel systematic calibration errors
- Spare instruments to monitor slow drift
- Wide angle cameras (solar/terrestrial) for separation, scene identification, ADM development, mapping
- Constellation to improve sampling, possibly combining precessing and sun-synchronous orbits
The Earth Climate Observatory (ECO) mission

1-2 satellites in precessing orbits:
- Good sampling of diurnal cycle on annual time scale
- Only annual means
- Single point of failure
- Mapping difficult

2 sun-synchronous + 1-2 precessing:
- Good sampling of diurnal cycle on annual time scale
- Monthly means + mapping possible
- Intercalibration
- Sensitive to failure

3-4 sun-synchronous + 1-2 precessing:
- Excellent sampling of diurnal cycle on annual time scale
- Cloud feedback monitoring
- Insensitive to failure

8, or more, sun-synchronous:
- Excellent sampling of diurnal cycle on daily time scale
- Footprints overlap, also in tropics
- Excellent mapping
- Robust to failure
## Summary of errors

ERBE non-scanner (from Wong et al. 2018):

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<tr>
<th>Sources of uncertainty</th>
<th>Longwave</th>
<th>Shortwave</th>
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<td>Instrument absolute accuracy</td>
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<td>± 1.0</td>
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<tr>
<td>Non-scanner inversion (mapping to TOA level)</td>
<td>&lt; ± 1.0</td>
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<tr>
<td>Satellite altitude correction</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Twilight data</td>
<td>n/a</td>
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~ 3.0 Wm$^{-2}$ per channel

From SRL-2 draft report
## Summary of errors

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**Preliminary ECO mission estimates:**

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<th>Sources of uncertainty</th>
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<tr>
<td>Instrument stability (drift per decade)</td>
<td>≪ ± 0.1</td>
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<tr>
<td>Instrument absolute accuracy on difference (preliminary)</td>
<td>&lt; ± 0.5</td>
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<td>Intercalibration (footprint mismatch)</td>
<td>n/a</td>
</tr>
<tr>
<td>Non-scanner inversion (mapping and reference level)</td>
<td>n/a</td>
</tr>
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<td>0.0</td>
</tr>
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<td>Twilight data</td>
<td>n/a</td>
</tr>
<tr>
<td>Polar regions</td>
<td>?</td>
</tr>
<tr>
<td>Diurnal cycle sampling (preliminary estimate)</td>
<td>≪ ± 0.3</td>
</tr>
<tr>
<td>Anisotropic correction (literature estimate)</td>
<td>&lt; ± 0.1</td>
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From SRL-2 draft report
Long term monitoring strategy

ECO mission nominal life time is relatively short (5-10 years), but the idea is that it can develop into a long term monitoring mission:

- Instruments are fairly simple, and most of the cost is in development
- Spare instruments can serve to:
  - Evaluate issues on ground
  - Quickly launch satellites in case of failure
  - Piggyback on other missions, synergies
  - Help improve future missions
  - Be shared with other space agencies
- Challenge: long term monitoring is not so cool
We are working towards answering an ESA Earth Explorer call next year.
Summary ECO mission

- We aim to provide accurate and robust long term monitoring of Earth’s **global mean radiation imbalance**
- Concept based on wide field of view radiometers using differential technique plus two cameras (Steven’s talk)
- Use of multiple identical instruments to reduce errors from calibration and drift
- Complementary, to more resolution-focussed “big” missions (spatial, temporal, spectral)
- [ long list of things it cannot do ]
- A ‘gap’ filler?
Extra slides
Anisotropic effects

Wide field of view radiometer measures actual flux at satellite position.

However, systematic biases in viewing- and actual flux at satellite position

Gristey et al. (2017) simulated a 32 satellite constellation to produce hourly maps.

Explored effects of anisotropic using TRMM angular dependence model (ADM).

Found difference when introducing ADM of 1.6 Wm\(^{-2}\) compared with isotropic case.

But only 0.1 Wm\(^{-2}\) between true and randomised ADMs.

\[ \pi^{-1} \int_0^{2\pi} d\phi \int_0^{\pi/2} d\theta R(\theta_0, \theta, \phi) \cos \theta \sin \theta = 1 \]

Mean: 0.98

Integral of ADM

0.0 0.2 0.4 0.6 0.8 1.0
Anisotropic effects

- We currently think the effect is small (~0.1 Wm\(^{-2}\))
- In this case we can apply a climatological ADM derived from cameras to correct for this small error
- In the unlikely event the effect is large, a correction using scene dependent ADMs may be needed

\[
\pi^{-1} \int_0^{2\pi} d\phi \int_0^{\pi/2} d\theta R(\theta_0, \theta, \phi) \cos \theta \sin \theta = 1
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