CloudSat – what we have learned and gaps

Graeme L Stephens
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Clouds – some progress

- Clouds are not where we thought they were this last 30+ years
- Light precipitation and snow and we now have reasonable measures of snow (at least in polar regions)
- We know how often it rains/snows - dreary models – we know by how much and why and more or less how to fix them
- We know much more about the cloudy nature of convection& are beginning to understand what the broader Earth science implications
- We know we there is a SW southern ocean bias and how to fix it

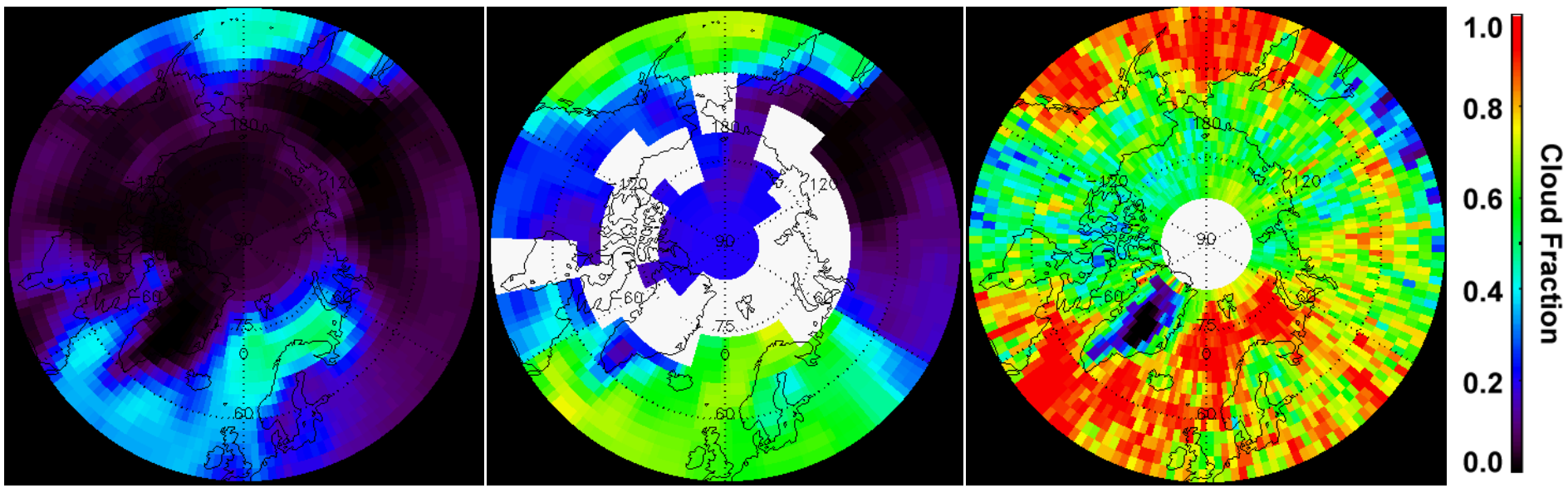
Polar clouds

DJF Low Cloud Maps

ISCCP D2
(infrared)

Warren
(surface obs.)

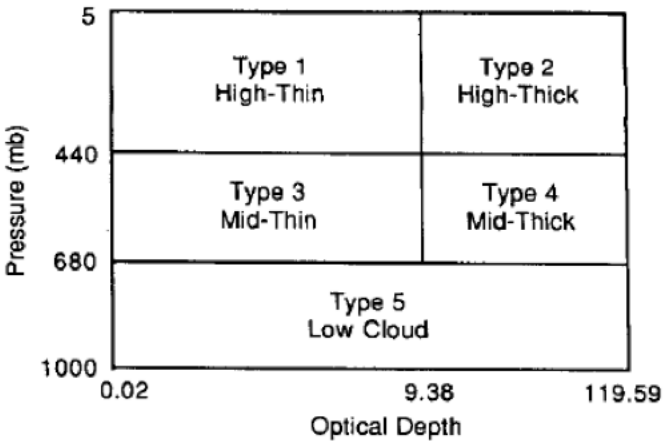
2B-Geoprof-lidar



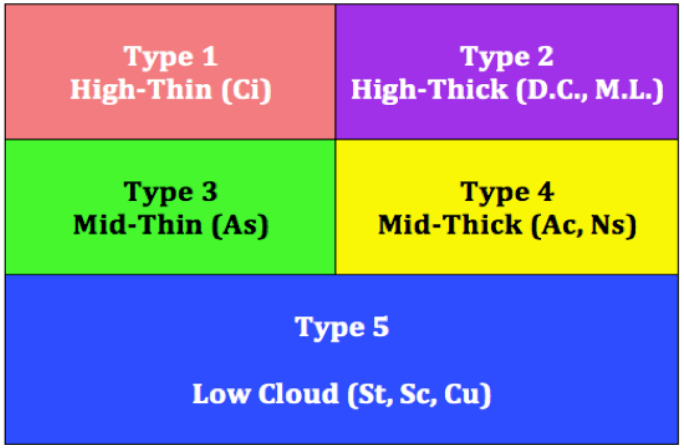
..a ‘different’ world emerged

Revisiting Partitioning

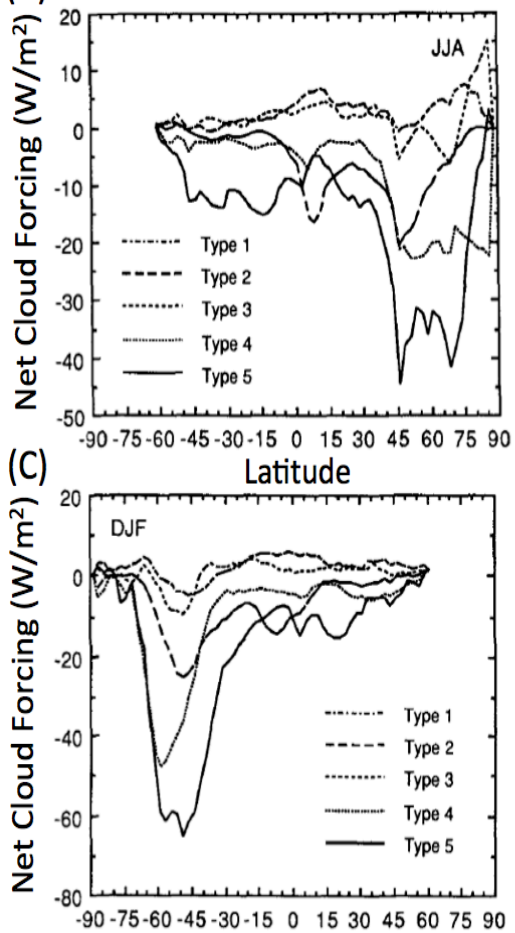
Hartmann et al (1992)



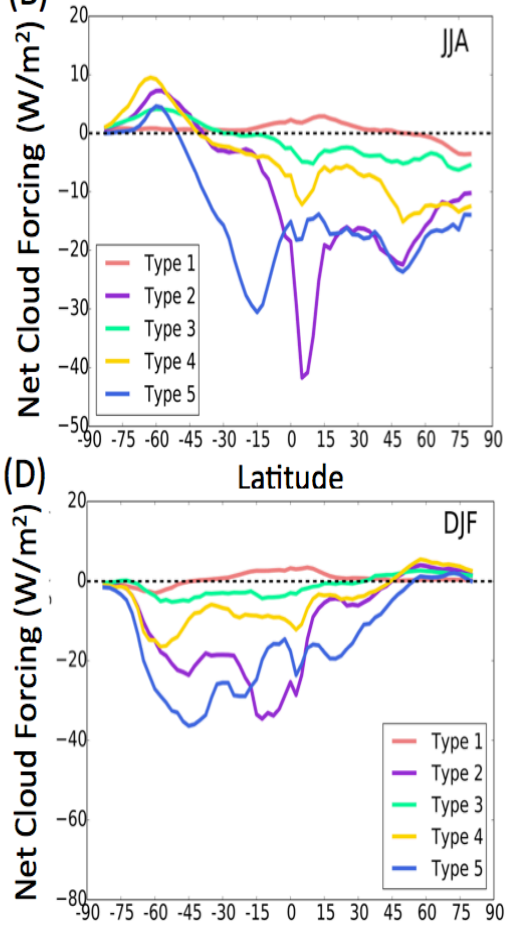
2B-FLXHR-LIDAR



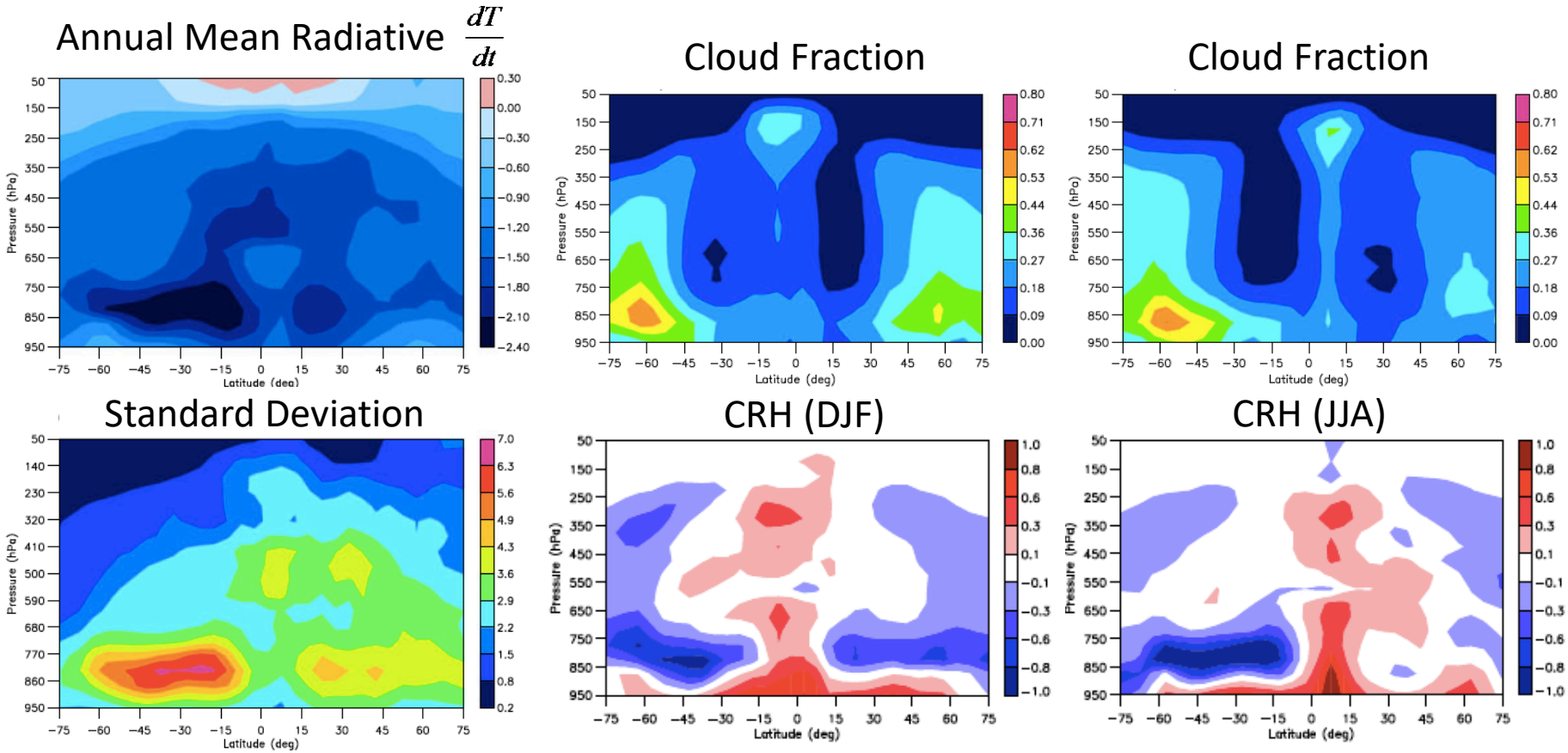
Hartmann et al (1992)



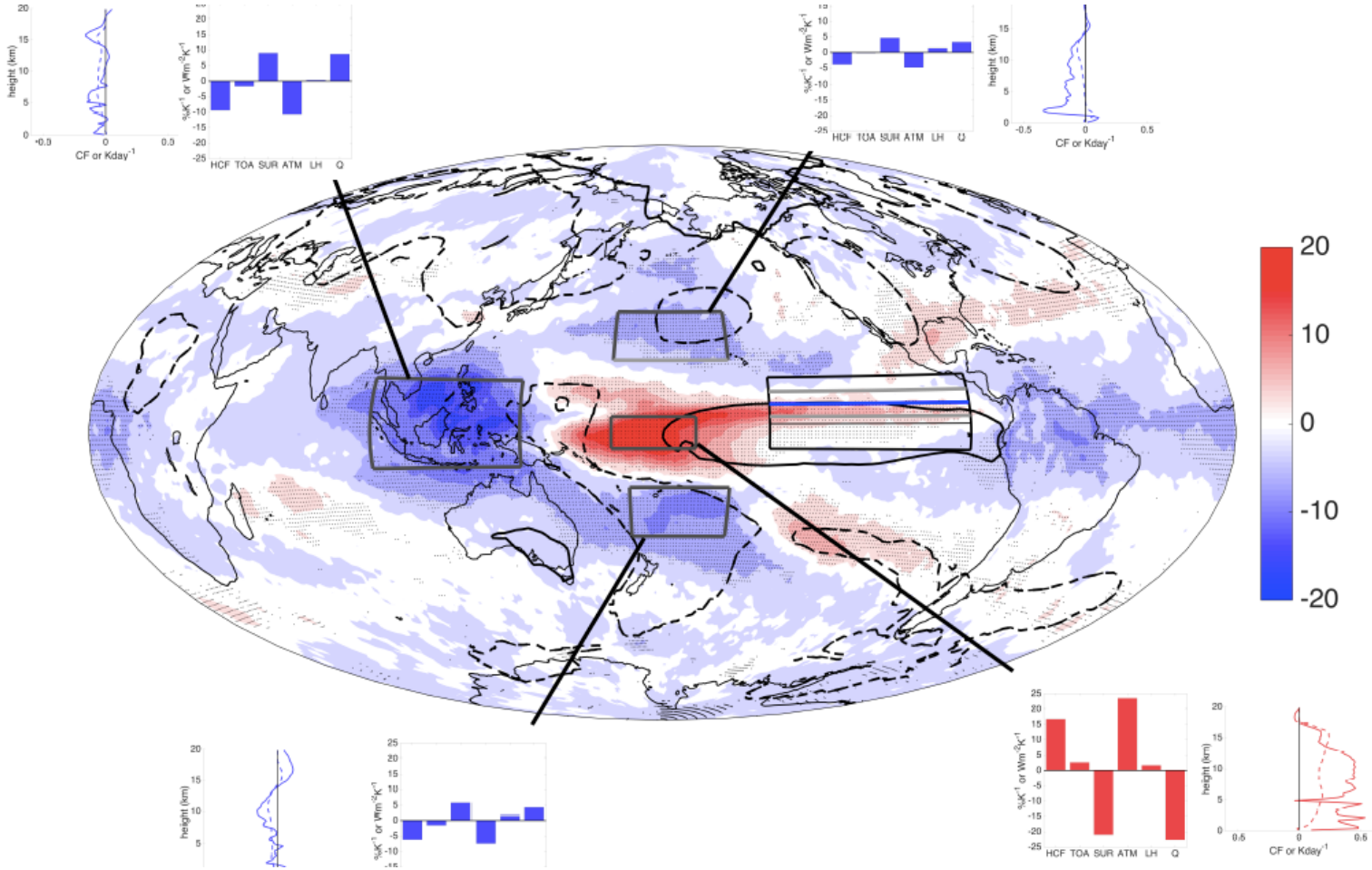
2B-FLXHR-LIDAR



The Vertical Dimension is crucial for understanding how clouds heat the atmosphere, how rain forms,…



Haynes et al., *Geophys. Res. Letters* (2013)


height (km)
CF or Kday^{-1}
%K^{-1} or Wm^{-2}K^{-1}
HCF TOA SUR ATM LH Q
20
10
0
-10
-20
%/K

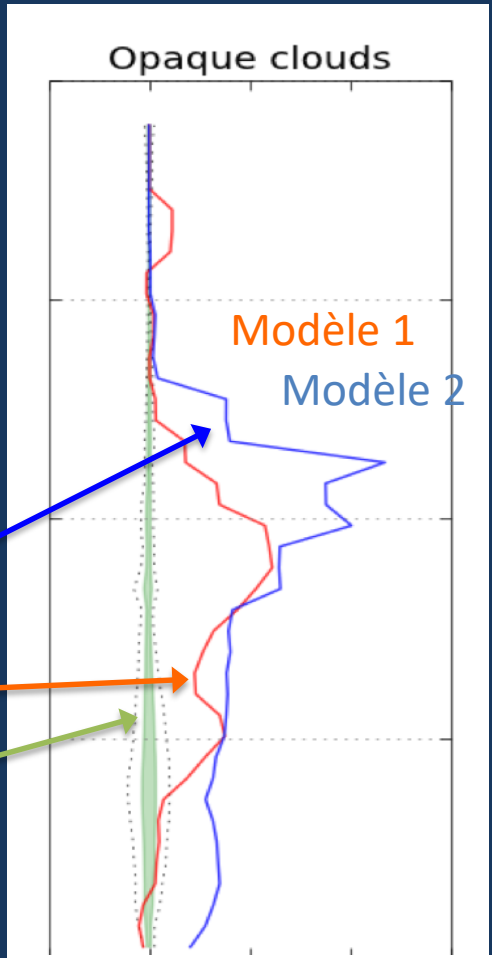
Cloud vertical distribution in a warming climate - this matters because it affects the hydrological cycle directly

The predicted forced changes in cloud vertical distribution (directly measurable by spaceborne active sensors) are much larger than the currently observed variability

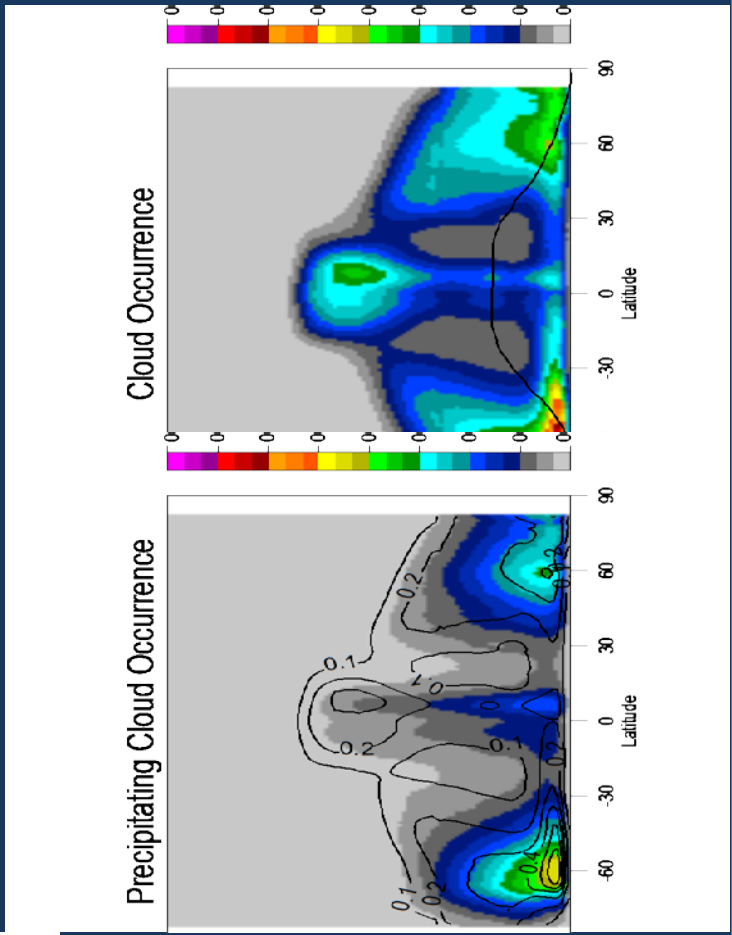
Model 2

Same, but for modèle 1

Observed natural variability



Cloud fraction anomalie(%)



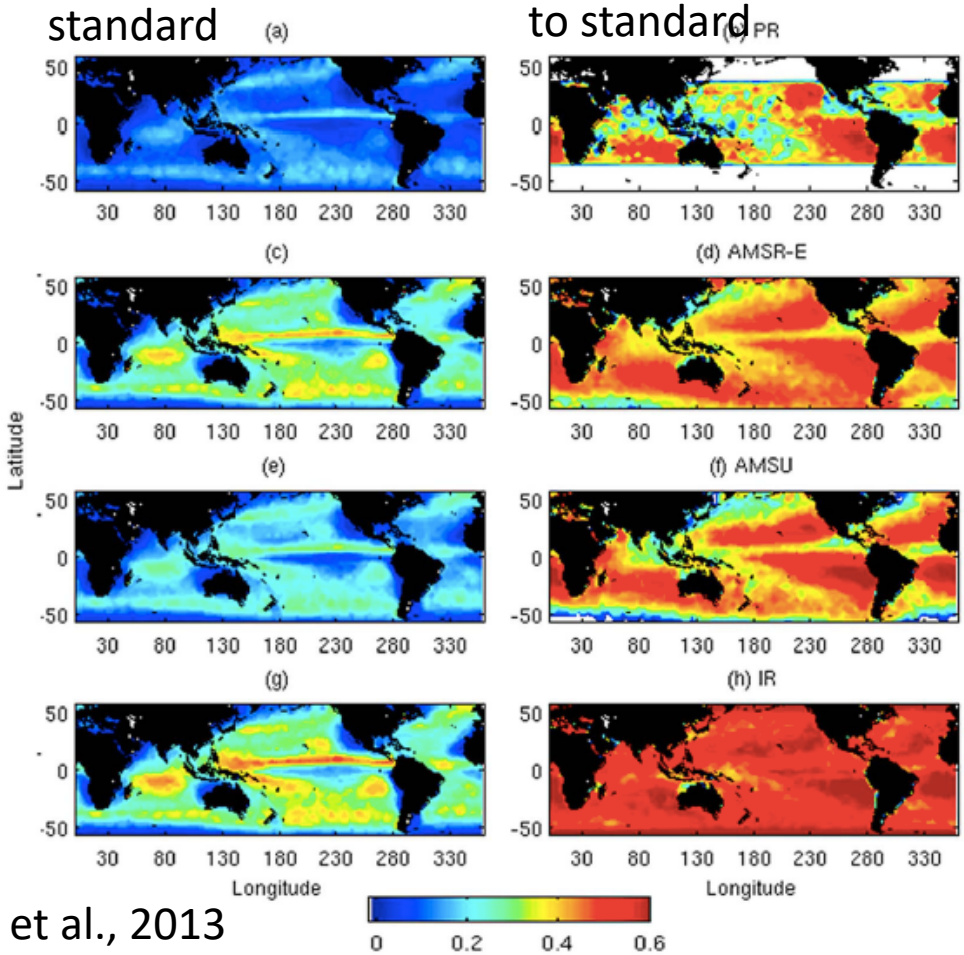
Chefner et al., 2014

Difference between the forced cloud fraction profile (+4K) and the cloud fraction profile in the current climate

Occurrence of precipitation (and cloud)

CloudSat as detection standard

Fraction missed relative to standard



Behrangi et al., 2013

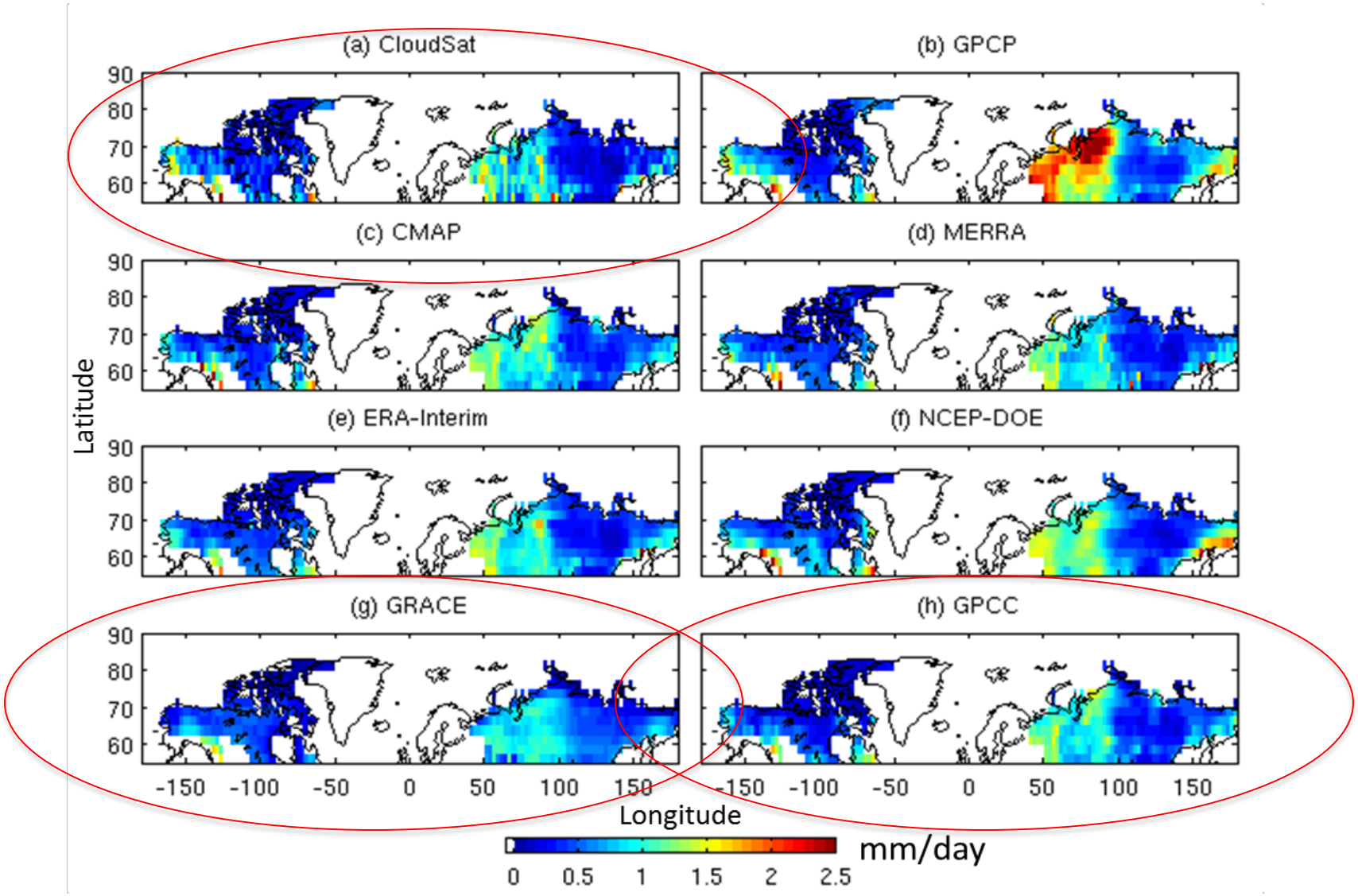
Figure 2. (a, c, e, and g) Maps of CS_b rain frequencies, corresponding to the footprint size of each studied sensor. (b, d, f, and h) Maps of fraction of missed rainfall (F_{mr}) for each sensor, calculated from equation (1) using its corresponding map of CS_b rain fraction. From top to bottom the rows represent maps for PR, AMSR-E, MHS, and IR, respectively. The results are based on 3 years (2007–2009) of rainfall data.

It is unrealistic to expect that we will gather precipitation sub-daily and on a kilometer scale purely from observations alone.

This information will likely come from advanced analysis systems.

The everywhere all the time

Genuine progress on frozen precipitation



ECMWF

What the last two decades has revealed is the viability of active systems - just as ‘affordable’ and just as reliable

Pros: Delivers vertical profiles and information that is much less ambiguous

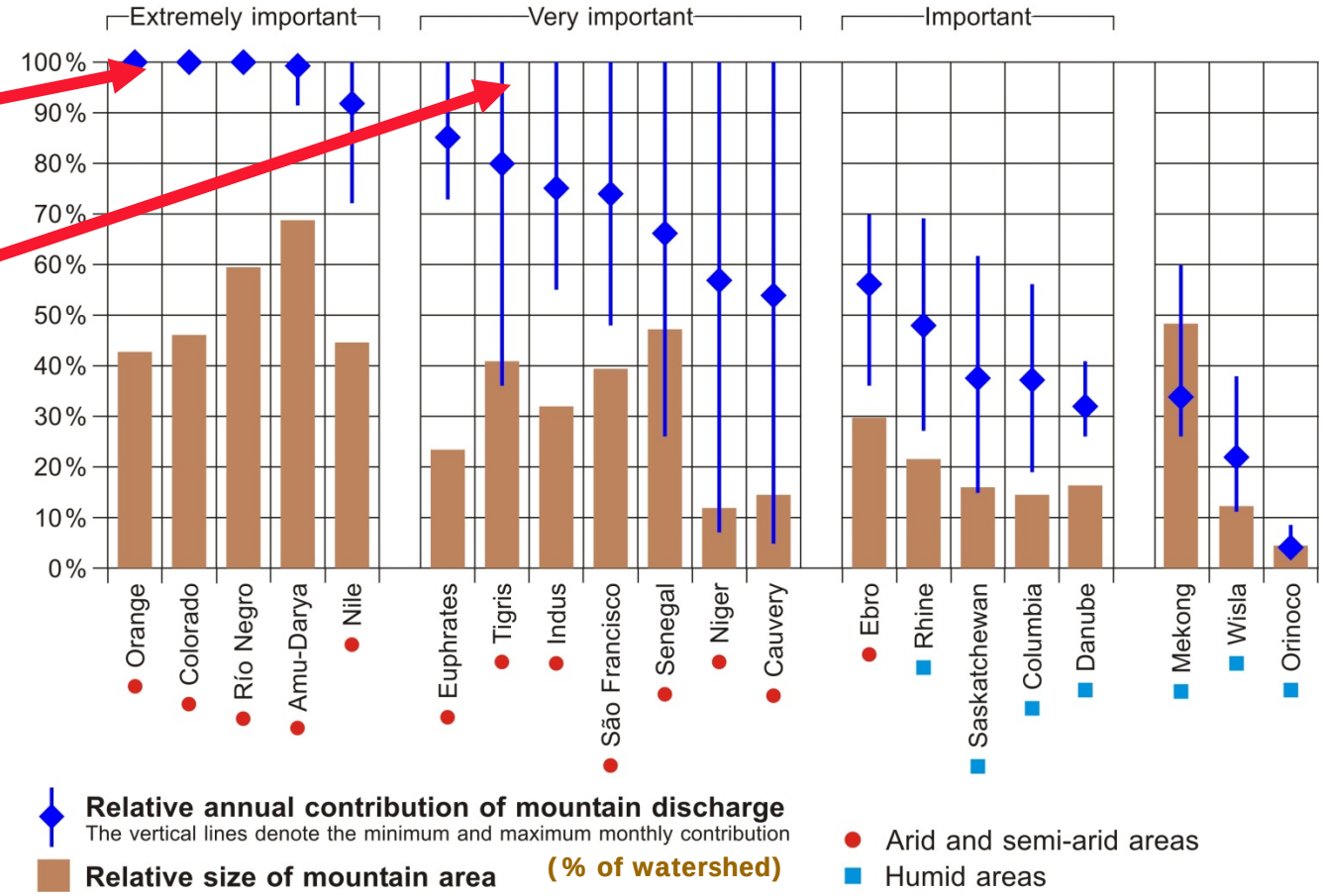
Cons: narrow swath, limited coverage

GAPS – how water moves in air

- Convection -
- Orographic precipitation

Mountains are important for water supply but poorly observed/monitored

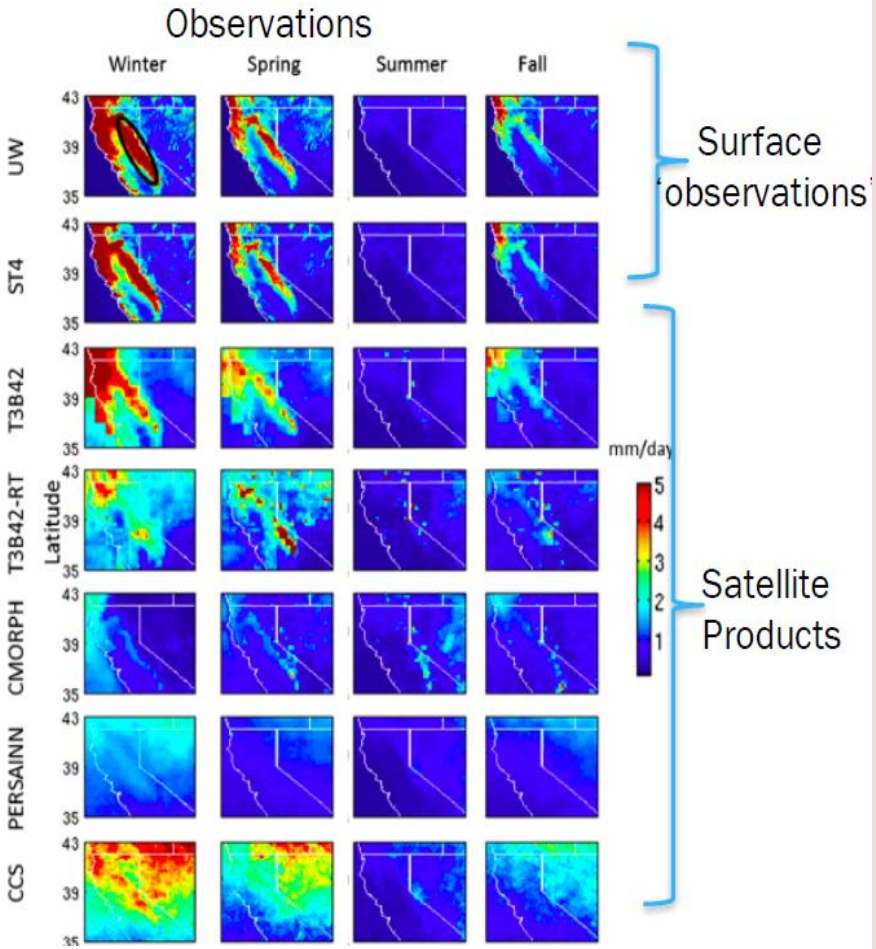
- ALL flow is from mountains
- Seasonal low flow is all from mountain regions



- **Outside of the tropics, mountains cover 24%**
- **of the surface, but yield 46% of the runoff.**

Vivroli *et at.*, 2003

The challenge of Orographic Precipitation:

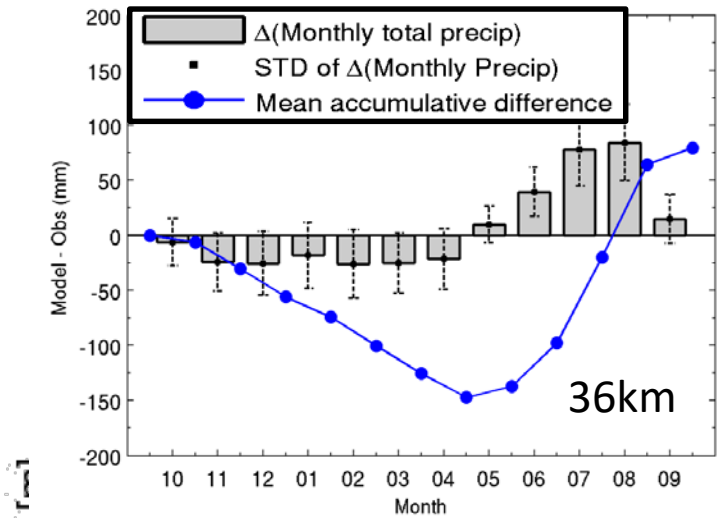


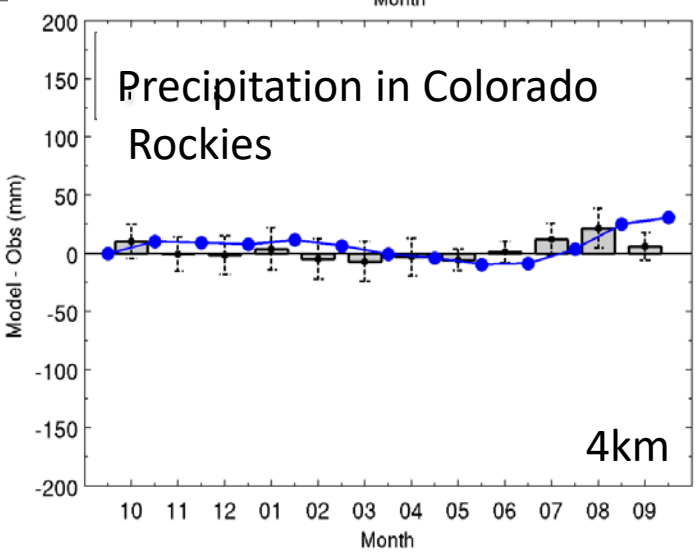
Behrangi et al. (JHM 2014)

Some key challenges:

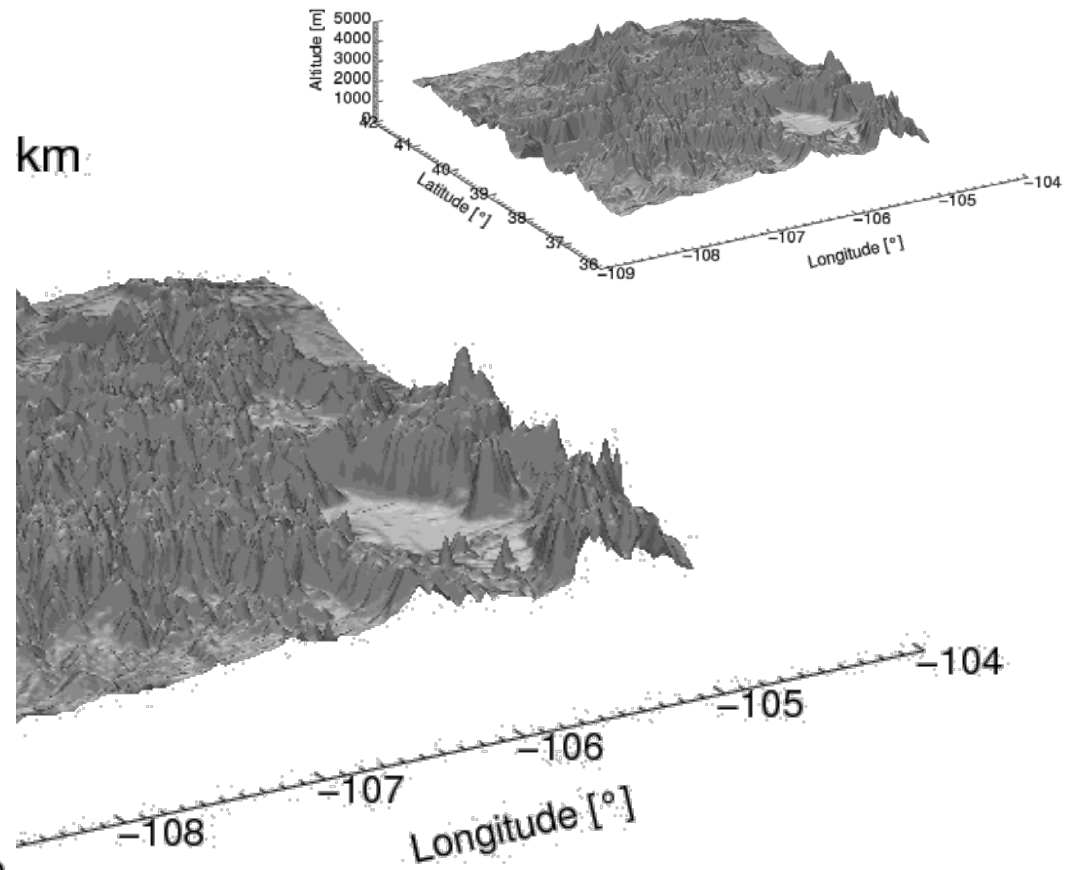
- Observing <u>orographic precipitation</u> remains a challenge for remote sensing of precipitation
- A large fraction of the precipitation falls in winter and as snow over mountains. Yet, <u>snow retrieval skill is limited</u> from space
- In practice <u>we don't determine precipitation phase from space</u>. It is based on established relationship between temperature and precipitation phase observed in stations. Given that temperature data is often from reanalysis and at coarse spatial resolution it can be a large source of uncertainty.
- High resolution modeling remains as a viable alternative to help

The model (r)evolution





Resolution : 2.4 km



30% too little winter precip & 65% too much in the & 40% too much ET

Courtesy Andy Prein

How bad can the rains be?

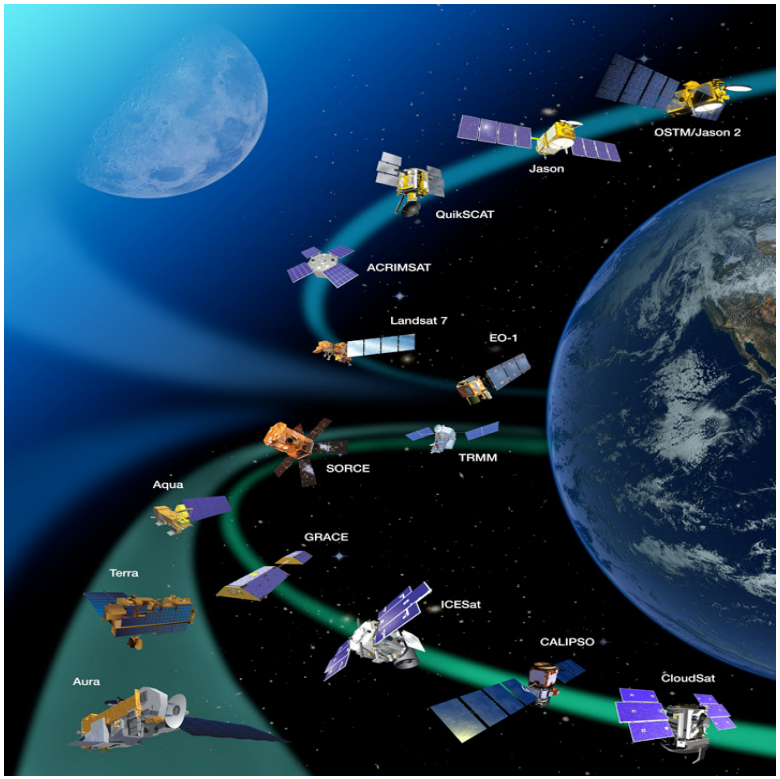
UK Minister to UKMO chief scientist

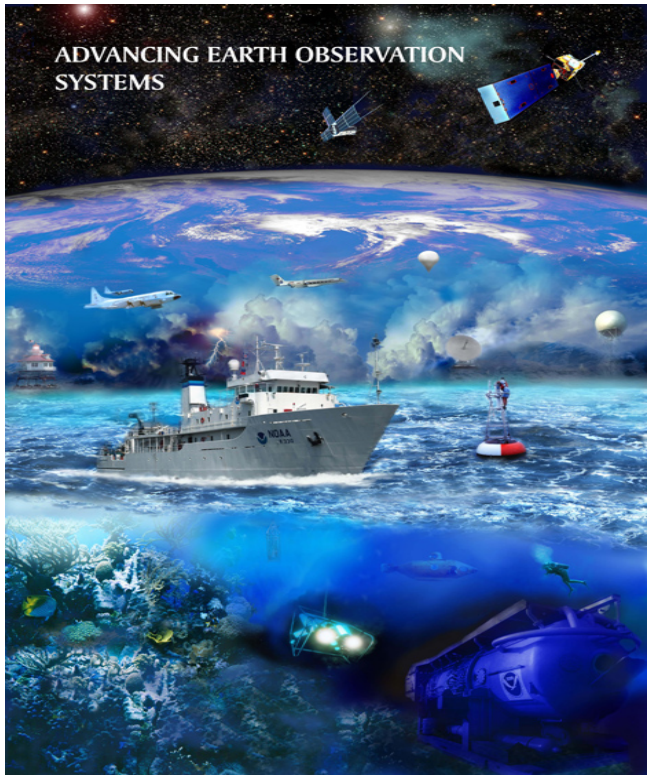
Tewkesbury flooding, July 2007

At some point we will evo
a more integrated system
which models and observa
on various scales and of
different types are more f
integrated.

This requires a more proce
viewpoint

A process-level perspective





We now know an immense amount about what is happening to the planet – but we don't necessarily know why

To understand why and translate this to model improvements that will lead to both better predictions and better analysis systems requires a more definitive 'process' understanding

Implication of the "process-oriented" model constraint

Suzuki, Golaz and Stephens (GRL '13)

Satellite-based constraint on μ-physics

This is one process example of jointly looking at clouds and precipitation that fundamentally addresses why models rain too much and its implication for climate projections

- r_{crit}=6.0μm : Temperature trend is best, but rain forms too quickly.
- r_{crit}=10.6μm: Rain formation is best represented, but temperature is too cool.
- The model reproduces the correct temperature trend only with flawed physics
- The rain inhibition (matching satellite) causes too much cooling: Why?

Challenges and opportunities

- The challenge
  - Is to develop a more systems approach to Earth Observations
  - Is to provide a sustained (&affordable) monitoring system
- The opportunities within the US
  - The US decadal Survey (a decade of planning and a broader international engagement)
  - Ventures opportunities
  - 'Technology revolution' - smallsats and miniaturization

Operational Earth observing systems (e.g. NOAA, USGS (Landsat), research Earth observing systems (e.g. NASA, competed (smaller) , and directed)

NASA Ventures program (competed)

Earth System science Pathfinder Ventures program – cost cap instruments and missions, selected at regular and well defined intervals

- Suborbital – EV-S ($30M cap)
- Instrument – EV-I ($120M cap (includes 30M class D and/or cubesat mission)
- Mission – EV-M (4 years, $150M cap)

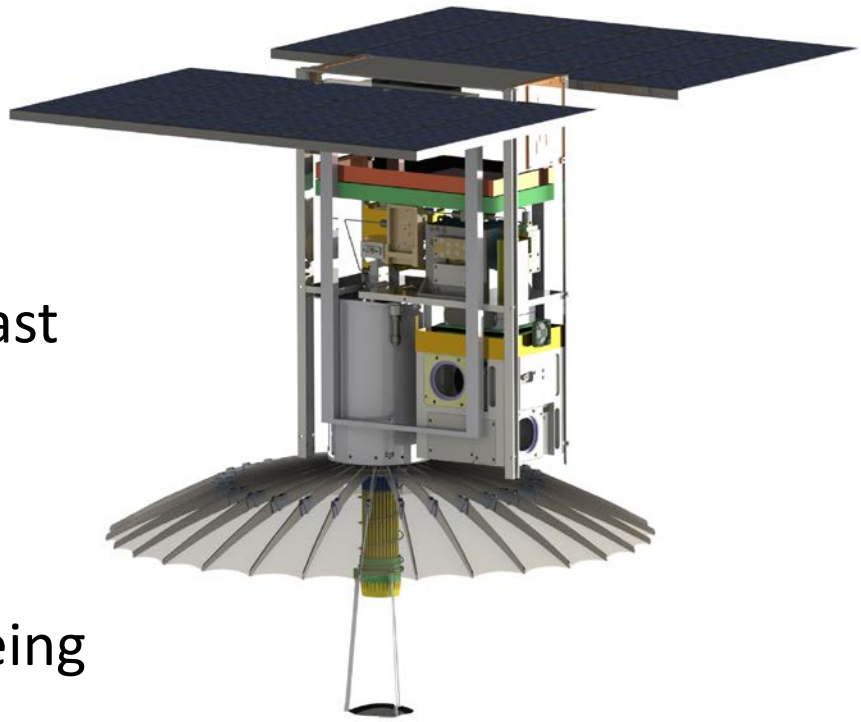
EV Solicitation Schedule

Solicitation Release Fiscal Year												
2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
EVS-1	(none)	EVM-1	EVI-1	EVS-2, EVI-2	(none)	EVM-2, EVI-3	EVI-4	EVS-3	EVI-5	EVM-3, EVI-6	(none)	EVI-7

Key
- EVS: Earth Venture Sub-Orbital solicitation
- EVM: Earth Venture Mission solicitation
- EVI: Earth Venture Instruments solicitation

RainCube Status

- The 1st-generation RainCube tech demo unit is being developed, and will be ready to launch in summer 2017
  - Main tech-demo is deploayable antenna
  - Plan for space operation for at least 6 months

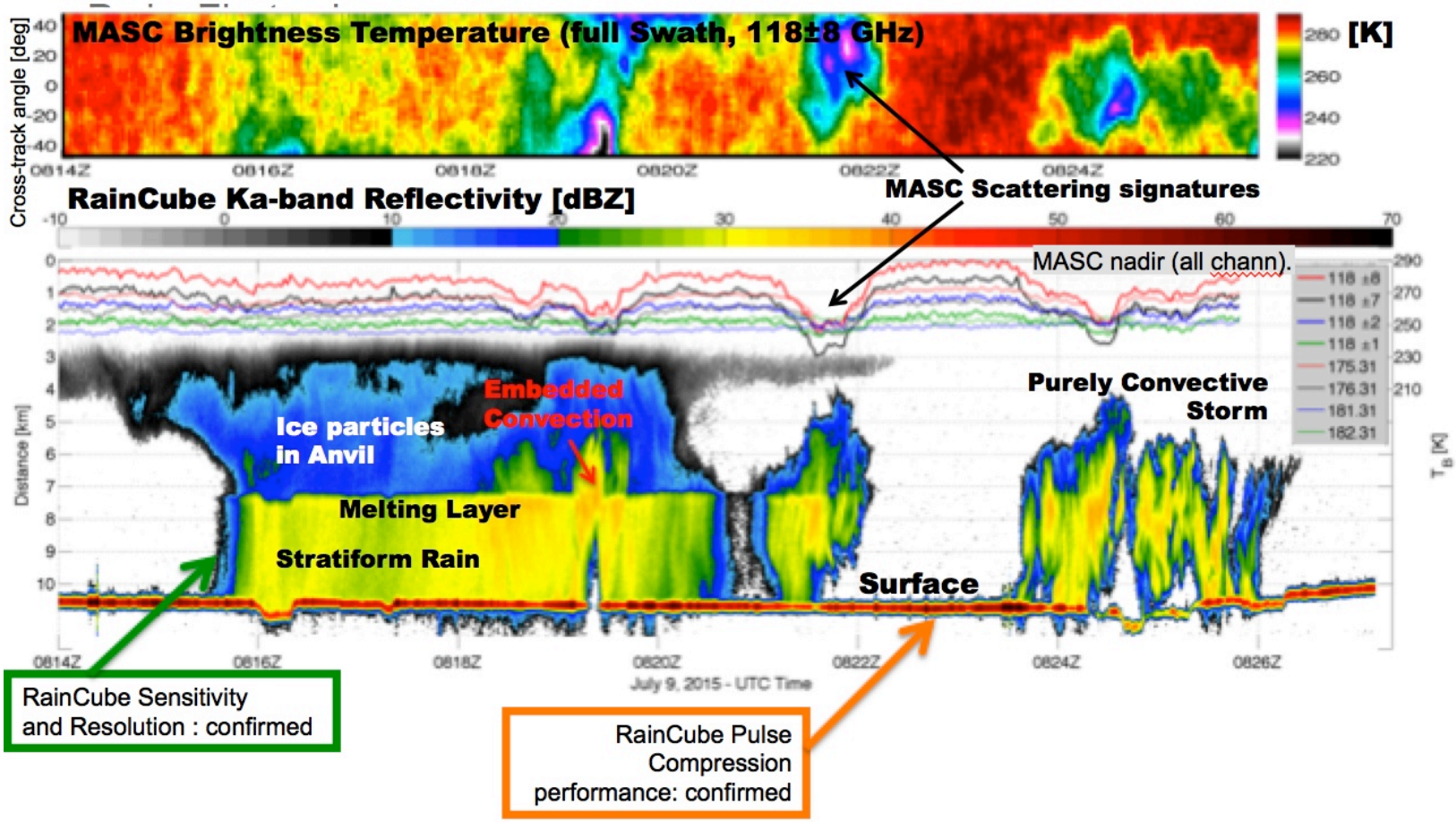


- Technologies for Second- and third-generation RainCube concepts are being developed
  - 1-m or larger deployable
  - Cross-track scanning
  - Doppler
  - Adaptation to 6-12U cubesats, and smallsats (D-Train).

RainCube Radar Electronics Capability Demonstrated

- Radar Electronics
  - Breadboard developed, tested and performance characterized.
  - Airborne flights have demonstrated performance
  - Hardware T/VAC & Vibe Qualifications done

Radar-Sounder observations of PECAN storms in July 2015

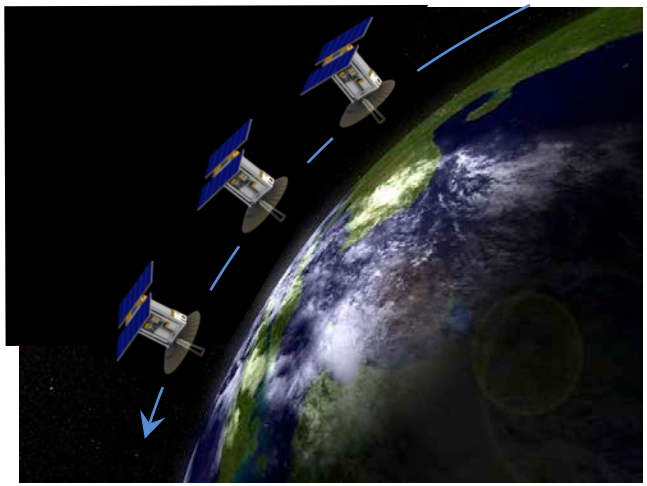


RainCube

- Precipitation radar from LEO from a cubesat sounding radar

RainCube matches (exceeds) the performance of the Global Precipitation Mission (GPM)'s Ka-band radar at a fraction of the cost, allowing many more precip radars to be flown in a constellation

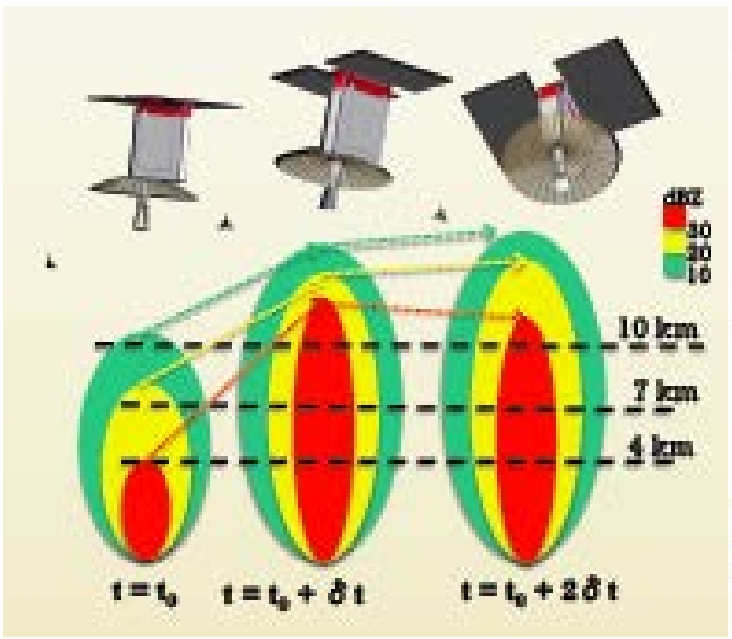
GPM Ka-band
Radar
1.4 meters (linear)
336 kg
344 W
5 km spatial
resolution

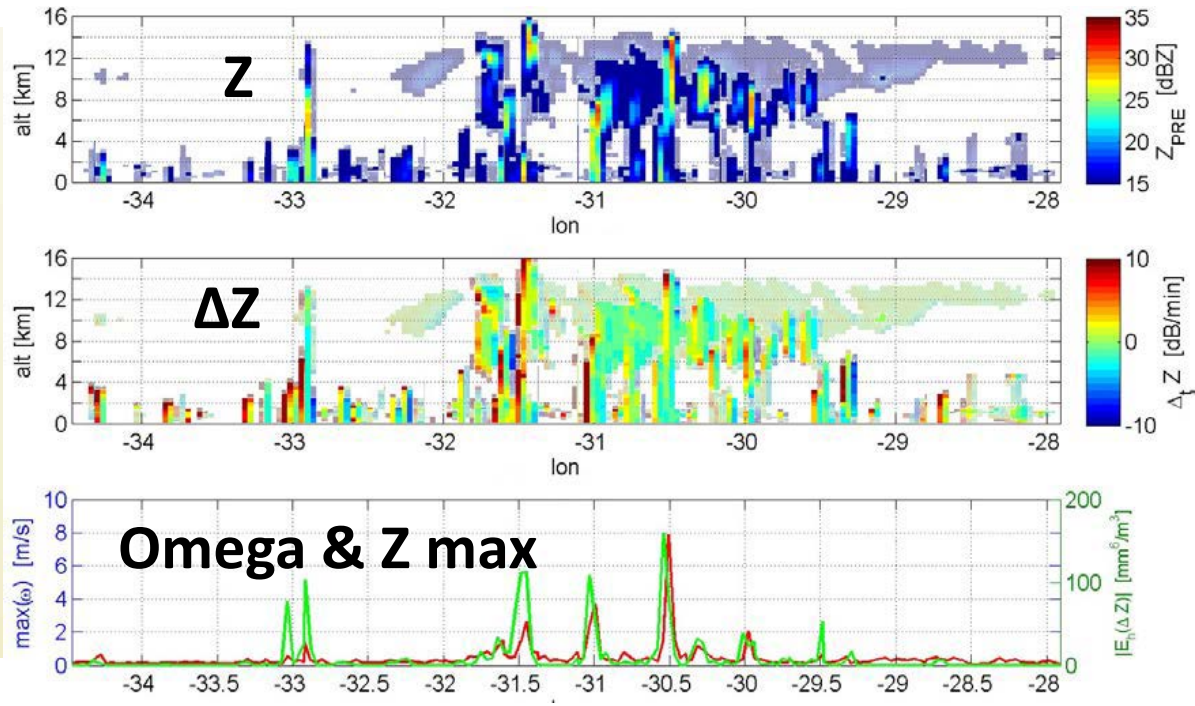


RainCube Ka-band Radar
30 centimeters (linear) 6U CubeSat
12 kg
30 W
5 km (horiz) / 250 m (range) spatial
resolution

Copyright 2015 California Institute of Technology. Government Sponsorship Acknowledged.

Clustered measurements: time differenced measurements probing processes – 'Raincube' on 50kg class minisat (fixed antenna)





- Provides more accurate measures of condensed mass because biases get removed
- Provides methods to estimate mass flux, previously unthinkable

Science questions

http://www.theclimatesymposium2014.com

Organised by:

WCRP World Climate Research Programme

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EO Recommendations

- Provide an **integrated observational strategy** that can be sustained over decades and supports understanding & development of (model) prediction tools. **(How? Mixture of lower cost systems- miniaturization with larger advances systems ?)**
- It should be shaped around **major science themes** and not around individual measuremens of variables. **(Consider in terms of major Earth system cycles?)**
- It should build upon operational observing systems and **filling gaps** in spatial and temporal monitoring **(e.g. requires obs and models integrated more effectively into an advanced analysis system - time resolution offers a new process dimension – more advanced Geo?)**
- Wherever possible take a **system-integrative approach (multi-disciplinary sensors, constellations, observation clustering …?) and p**Promote the **fusion of theory, observations and models (new analysis systems)**
- Incorporate and innovate **new technologies** and take advantage of opportunistic observations **(new capabilities, miniaturization, lower cost systems, …)**
- **Foster a strategic planning process** that combines science priorities and observational capabilities to deliver the most cost-effective return on investment **(national & international coordination)**

Earth system cycles

- Energy
- Water
- Bio-geochemistry

Extreme

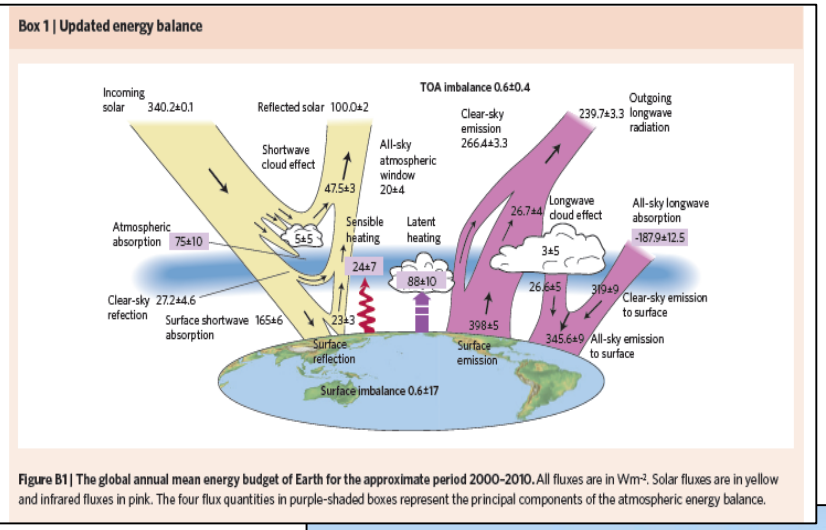
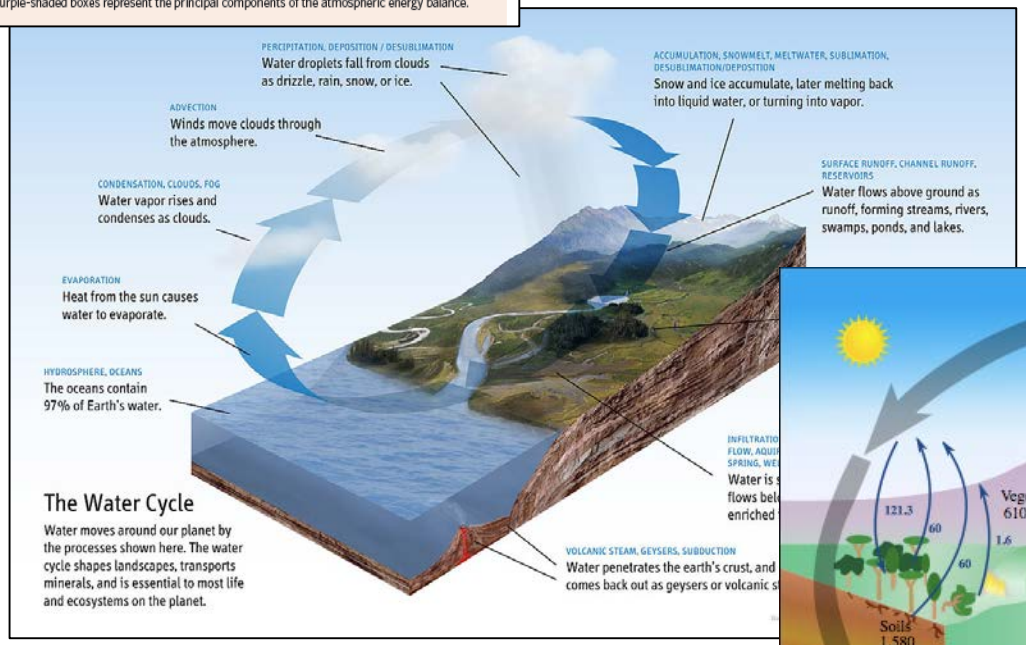
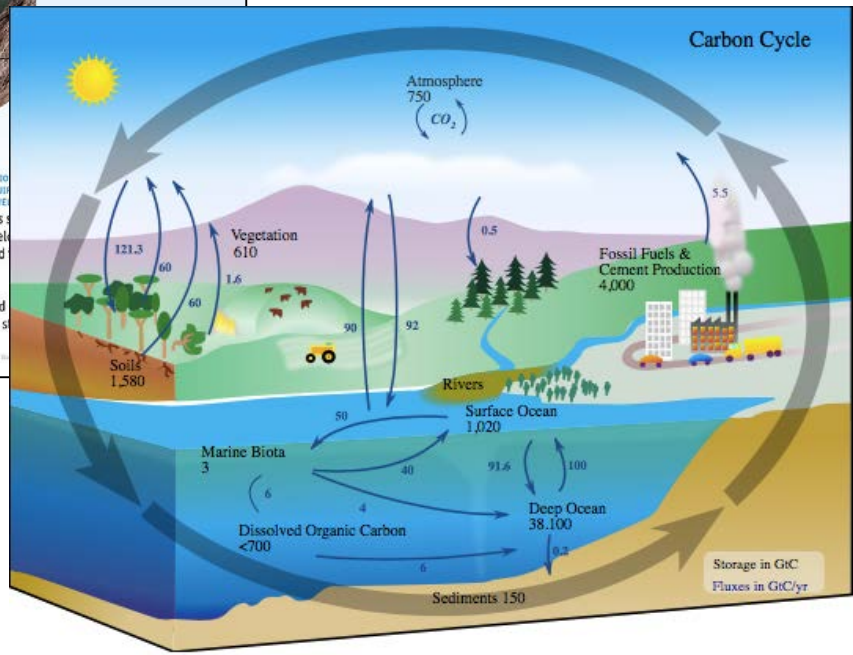


Figure B1 | The global annual mean energy budget of Earth for the approximate period 2000–2010. All fluxes are in Wm^{-2}. Solar fluxes are in yellow and infrared fluxes in pink. The four flux quantities in purple-shaded boxes represent the principal components of the atmospheric energy balance.





Big Science Questions *

(1) Where does all the heat go?*

(2) How is the fresh water changing?*

(3) Where does the carbon go?

* Dame Julia Slingo, Climate Symposium, 2014

WHY MONITOR THE CLIMATE?

BY RICHARD GOODY, JAMES ANDERSON, THOMAS KARL, ROBERTA BALSTAD MILLER, GERALD NORTH, JOANNE SIMPSON, GRAEME STEPHENS, AND WARREN WASHINGTON

BAMS, 2002

A societal need for greater confidence in long-range climate projections requires a monitoring program that can provide systematic and objective tests of the predictive capabilities of climate models.

- ❑ **Explain the Past**
- ❑ **Understand the Present**
- ❑ **Predict the Future**

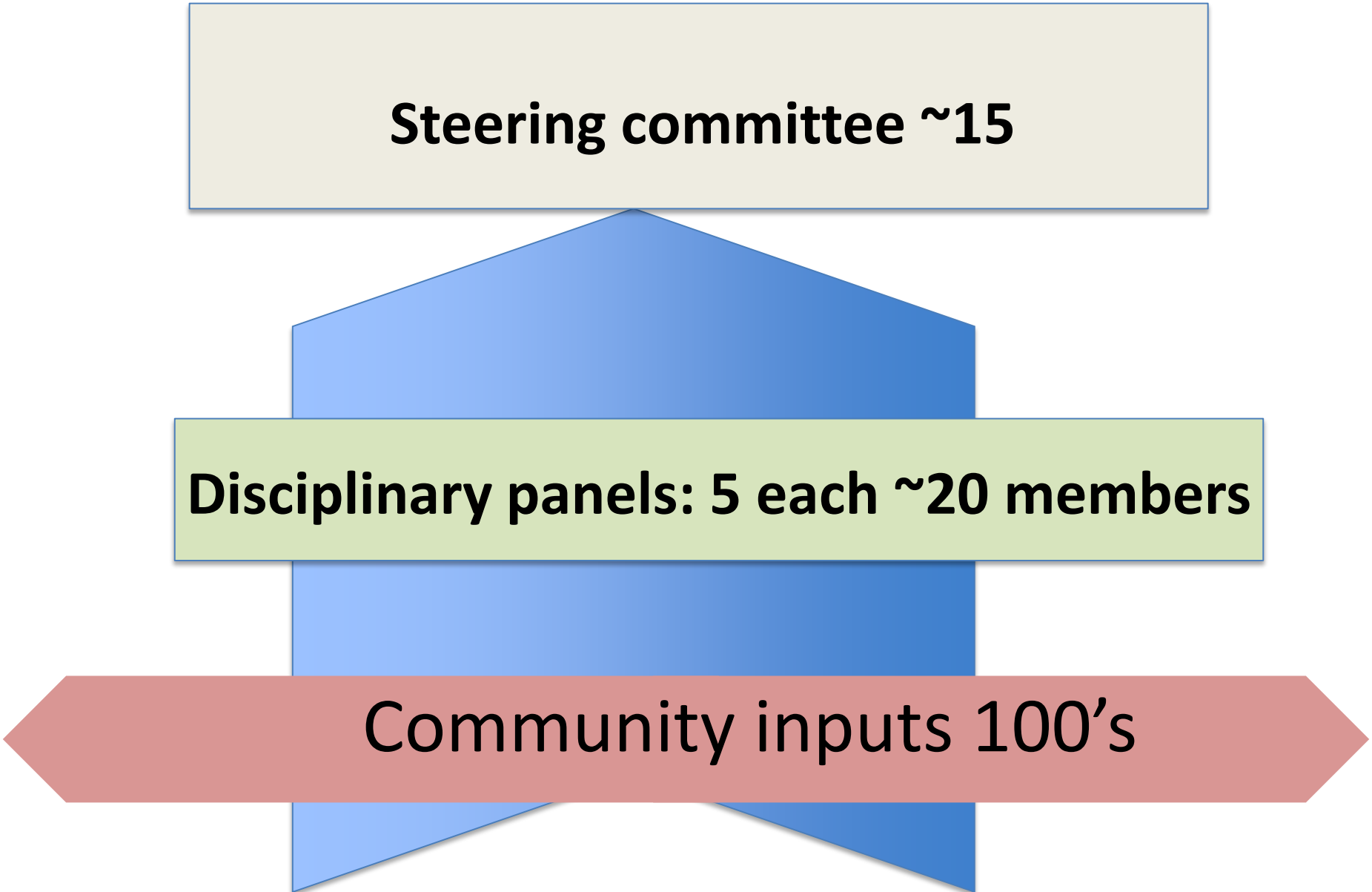
Charting the course for the next decade of Earth observations
nas.edu/esas2017
The '2017 Decadal Survey -
directed missions
The National Academies of
SCIENCES · ENGINEERING · MEDICINE

The 2017-2027 ESAS

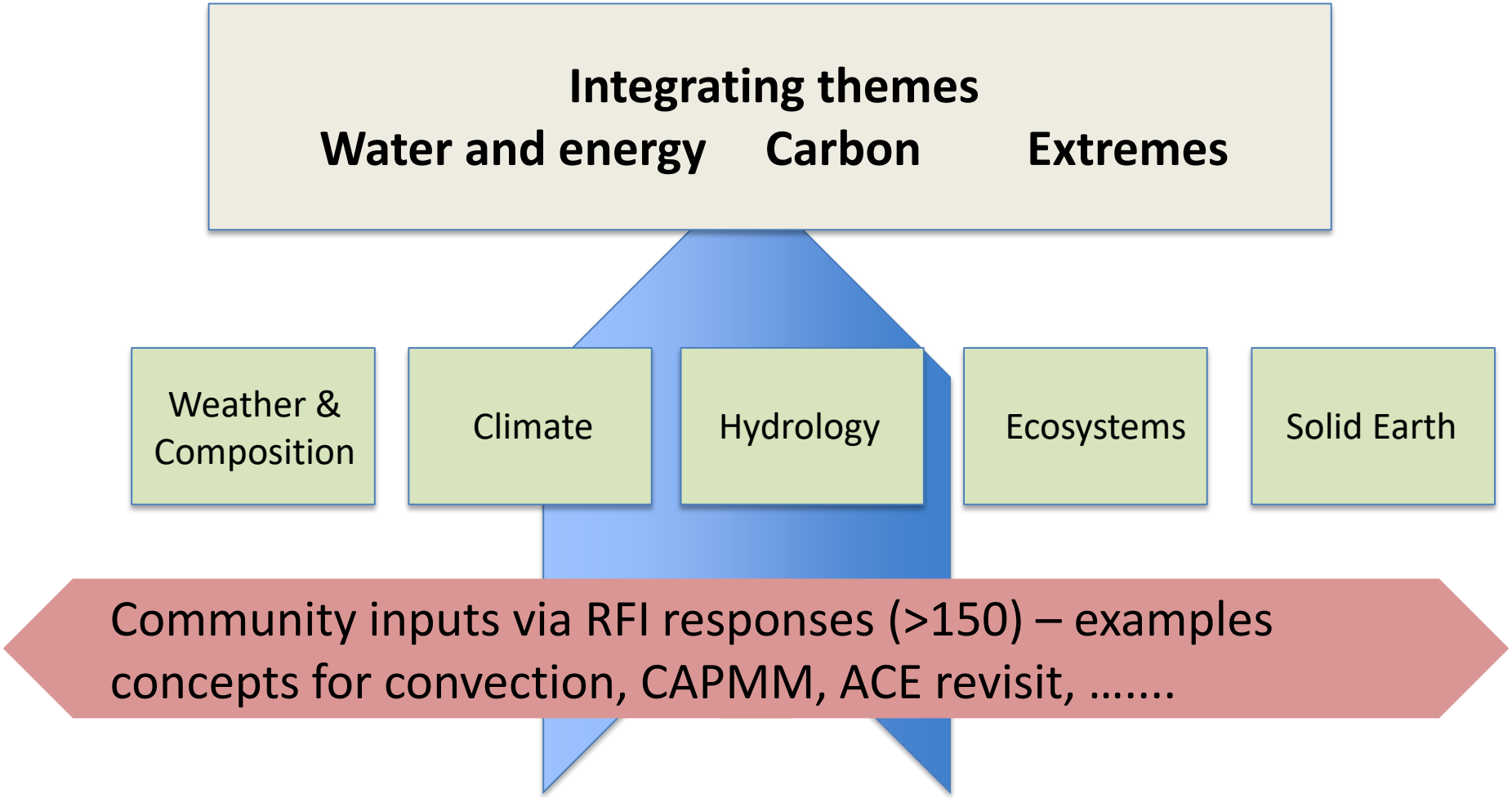
- Review progress of past decade,
- develop a prioritized list of top-level science and application objectives,
- Identify gaps and opportunities (NASA, NOAA, and USGS)
- Recommend approaches to develop a robust, resilient, and appropriately balanced U.S. program of Earth observations.
- Consider: Science priorities, implementation costs, new technologies and platforms, interagency partnerships, ***international partners***, and the *in situ* and other complementary programs carried out at NSF, DoE, DoA, DoD.

Involves heavy (international) community engagement in measurement concepts (~150 RFI responses) panels to review measurements and themes - the emphasis is on developing an integrated Earth system observing strategy and is being developed around science 'themes' (water, extremes, carbon, …)

ESAS17 structure



ESAS17 structure



CAPMM white paper

Prepared by cloud and precipitation communities

Three basic questions posed under these challenges are:

- how will the availability of fresh water change in the coming decades?
- what is the predictability of changes in frequency and intensity of extremes at seasonal to decadal time scales?
- how does convection shape cloud feedbacks?

This requires a paradigm shift away from our current practices that largely observe “states” to future observing strategies that can deliver information on both states and “processes”.

Discussion of beyond CloudSat, beyond EarthCARE and beyond GPM: A US perspective

- A few comments on clouds
- A few comments on precipitation
- A few comments on processes

And later

- A few comments on the Darmstadt 2014 climate symposium
- A few comments on the US path forward – the NRC Earth Science and Applications Study (ESAS 2017) aka 'Decadal Survey'