Open Challenges In Water Cycle Science (Remote Sensing)

Dara Entekhabi
MIT

Satellite Observations of the Global Water Cycle Workshop
March 7-9, 2007

SPACE NEWS
February 19, 2007

for in the report.

No U.S. government officials were called to testify at the hearing. But NASA Administrator Mike Griffin, speaking at a National Space Club luncheon the week before, delivered a brief pre-buttal of the report's central recommendation.

"I want you all to make sure that your pulse rate doesn't rise exorbitantly. A group of discipline specialists have recommended in all solemnity that their discipline needs more money. I am sure you are shocked to discover gambling in this casino, right?" Griffin said. "Leaving that aside, of course, I take very seriously the prioritization of tasks to be accomplished in the decadal survey and we will follow that just as closely as possible."

1. Is Earth Science Just Another Disciplinary Specialty?

2. Do We Monitor The Environment For Our Amusement?

Topics Covered Here:

- Major Gaps in Understanding.
- What Happens if We Never Know?
- What it Takes to Solve the Problem?

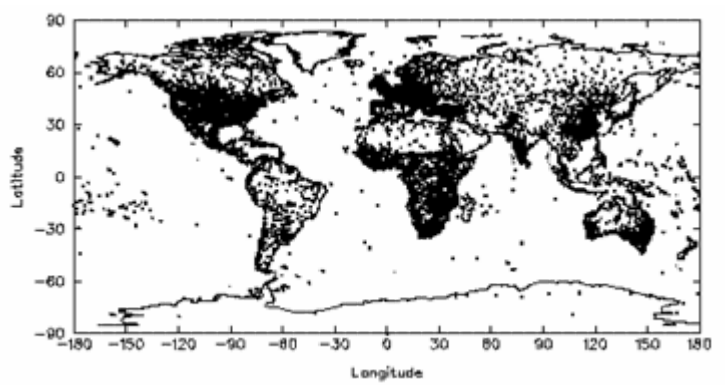
Taking Stock:

Achievements So Far.

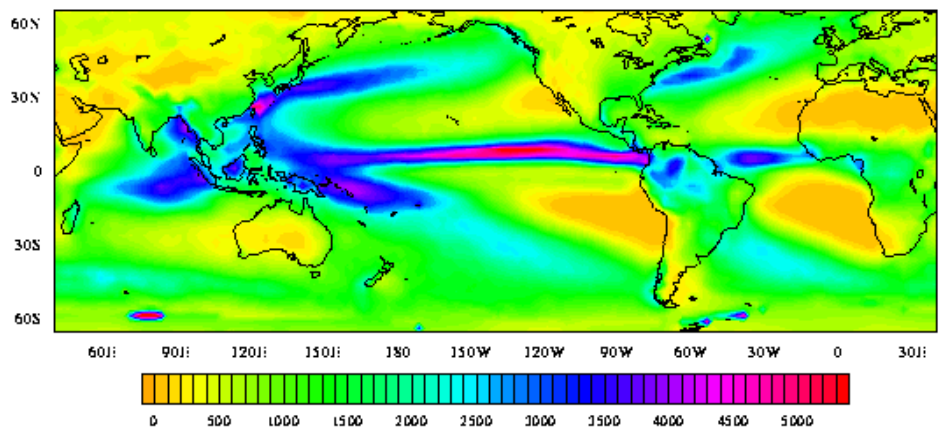
What They Made Possible.

1. Ocean Precipitation

- Catalyst in Understanding Air-Sea Interaction
- Atmospheric And Ocean Sciences as One Science
- Opened Era of Seasonal Prediction as Practical Outcome



Precipitation Gauges



MSU-TOVS

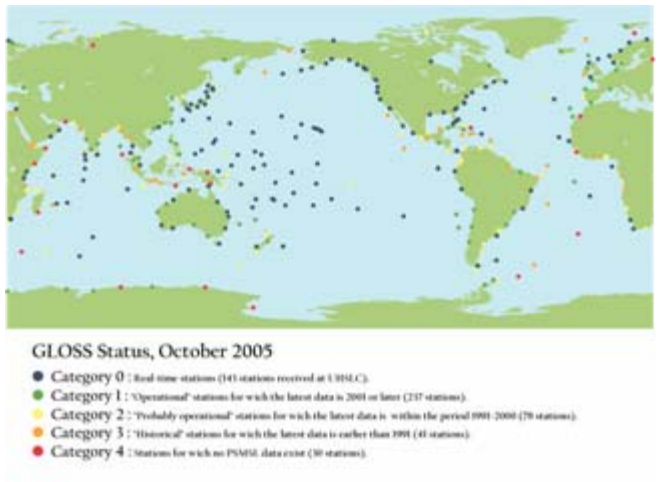
Taking Stock:

Achievements So Far.

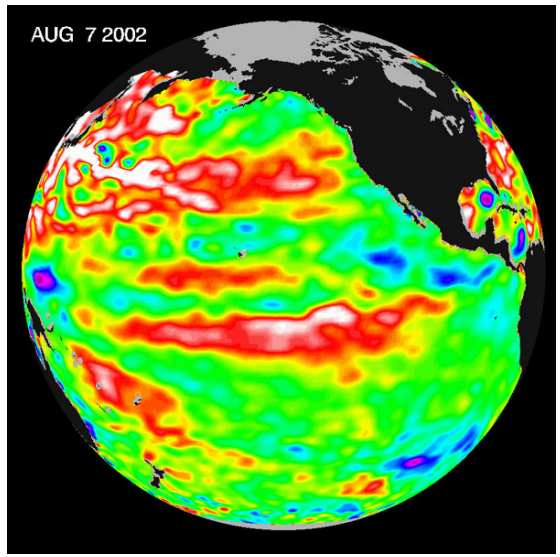
What They Made Possible.

2. Ocean Height

- Eddy-Dynamics Replaces Conveyer-Belt
- Pacific Basin Air-Sea Coupling Picture Complete
- Launched The Field of *Ocean Weather* as Practical Outcome



Tide Gauges



JASON

Taking Stock:

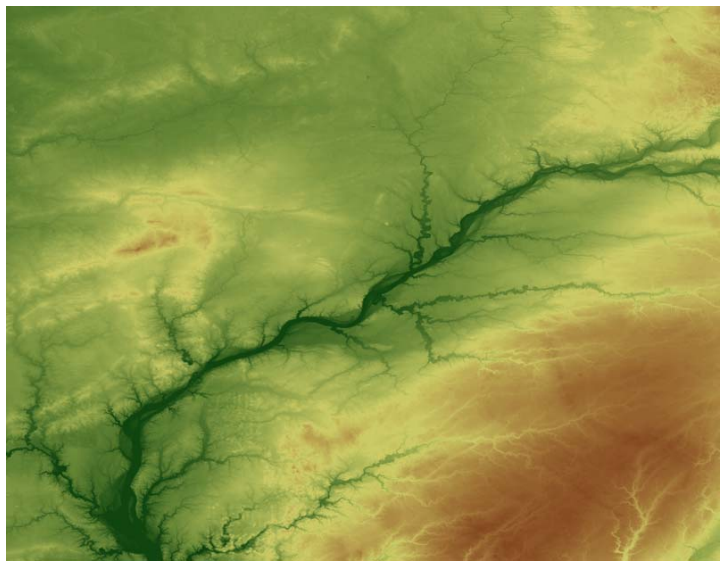
Achievements So Far.

What They Made Possible.

3. Digital Elevation

- Enables Spatial Hydrologic Modeling
- Linked Continental Hydrology and Oceans
- First Tool in Characterizing a Problem

USGS Quad



SRTM

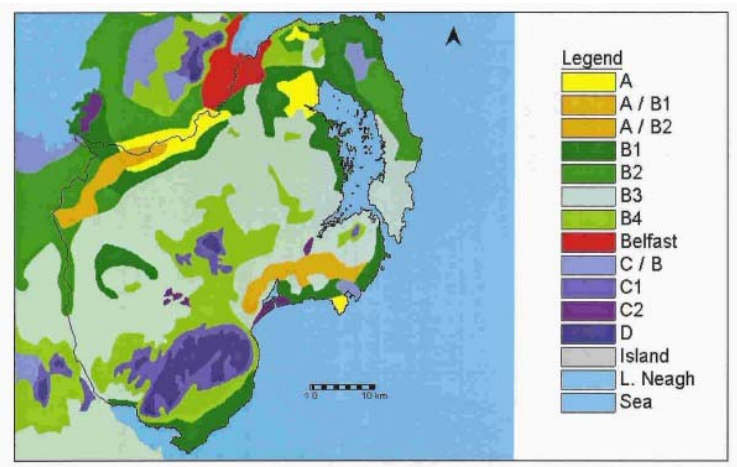
Taking Stock:

Achievements So Far.

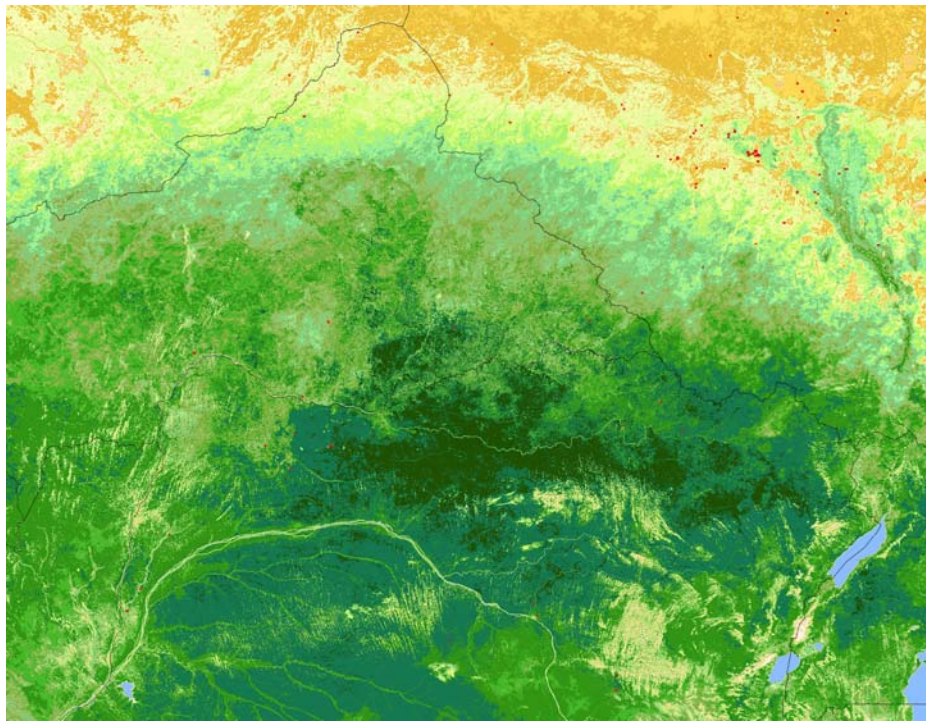
What They Made Possible.

4. Plant Vigor

- Terrestrial Biosphere Now Dynamic Component of Earth System
- *Global Ecology* Emerges as a Discipline



Land Classification



AVHRR-NDVI

Taking Stock:

Achievements So Far.

What They Made Possible.

4. And More…

The Point is That The Global Perspective Afforded by Remote Sensing Have Been Transformational For The Sciences.

Not Just More Data For The Science.

Observations That Invent New Scientific Disciplines/ Applications.

Looking Ahead

Most-Probably the Grand-Challenge Questions of Water Cycle Science are Derived From:

1. **Earth System With Human as a Principal Agent**

   (Impacts on par With Variations in Orbit, Sun, Tectonics)

2. **Heteorogeneous Processes and the Prediction-Uncertainties They Create**

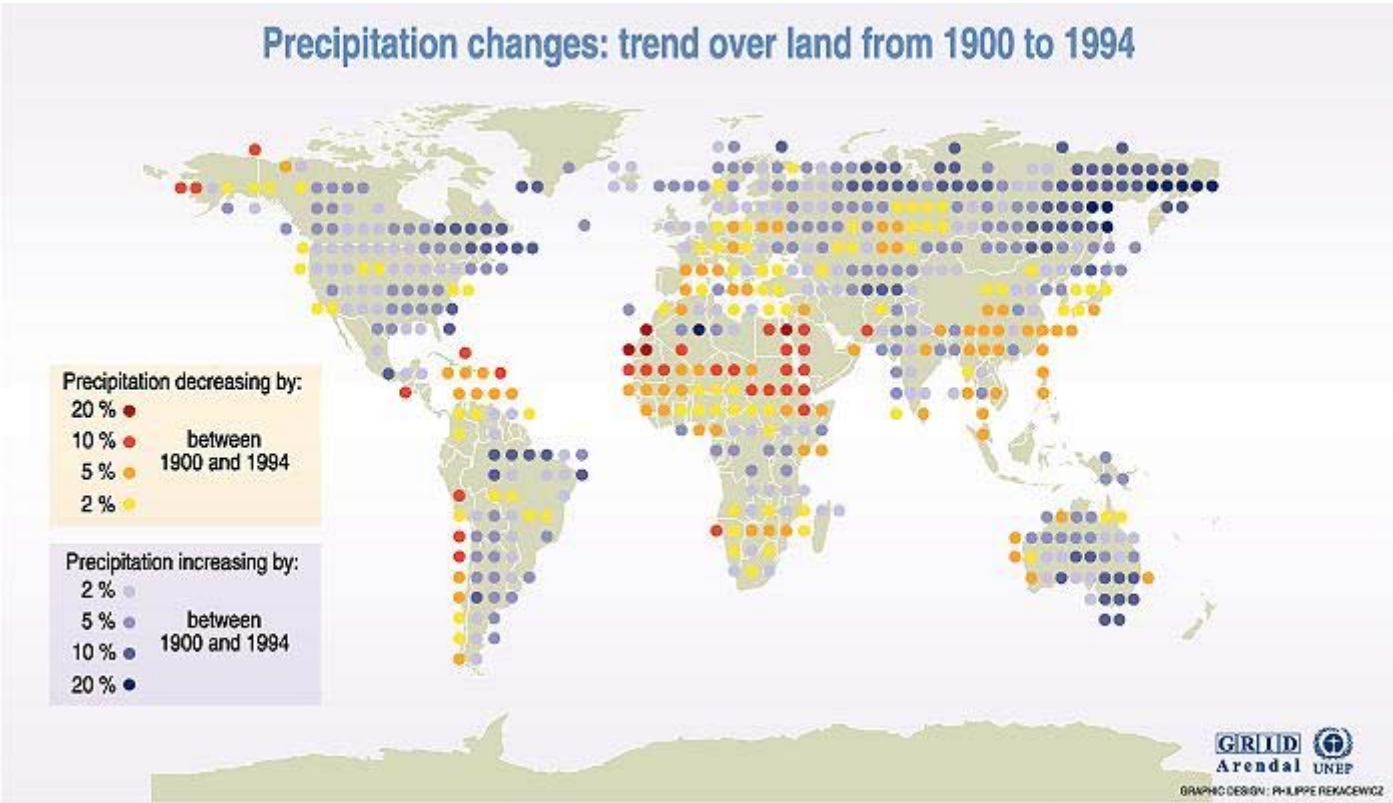
   (Nucleation, Chemistry, Other Unresolvables)

Humans as a Principal Agent

So Have Human Changes to Landscapes and Atmospheric Composition Changed the Water Cycle?

Precipitation as a Water Cycle Rate:

- Impact of Anthropogenic Aerosols and CCN?
- Impact of Enhanced Greenhouse Effect?



Looking Further…

Evaporation and Recharge

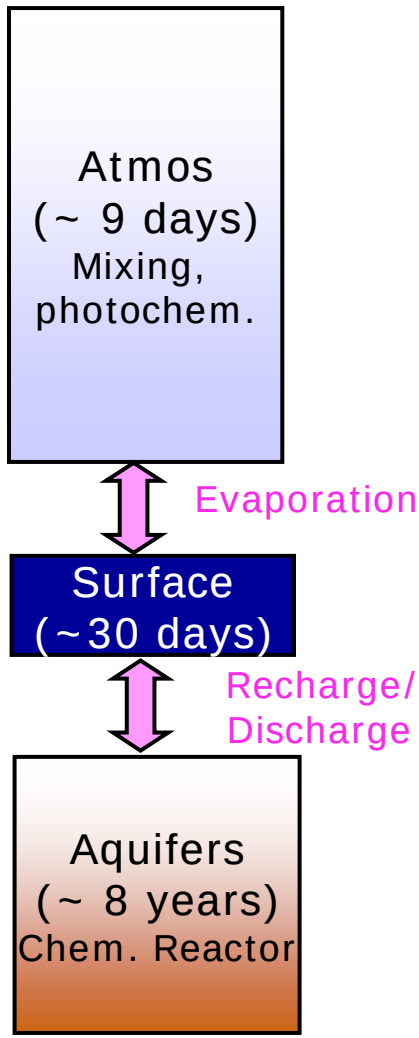
1. Fluxes that are first-order determinants of biogeochemical cycles

2. Fluxes that link the slow and fast components of the water cycle

3. Fluxes that to first-order determine and are determined by vegetation distribution

4. Fluxes that limit rate of sustainable use of surface waters and groundwater aquifers

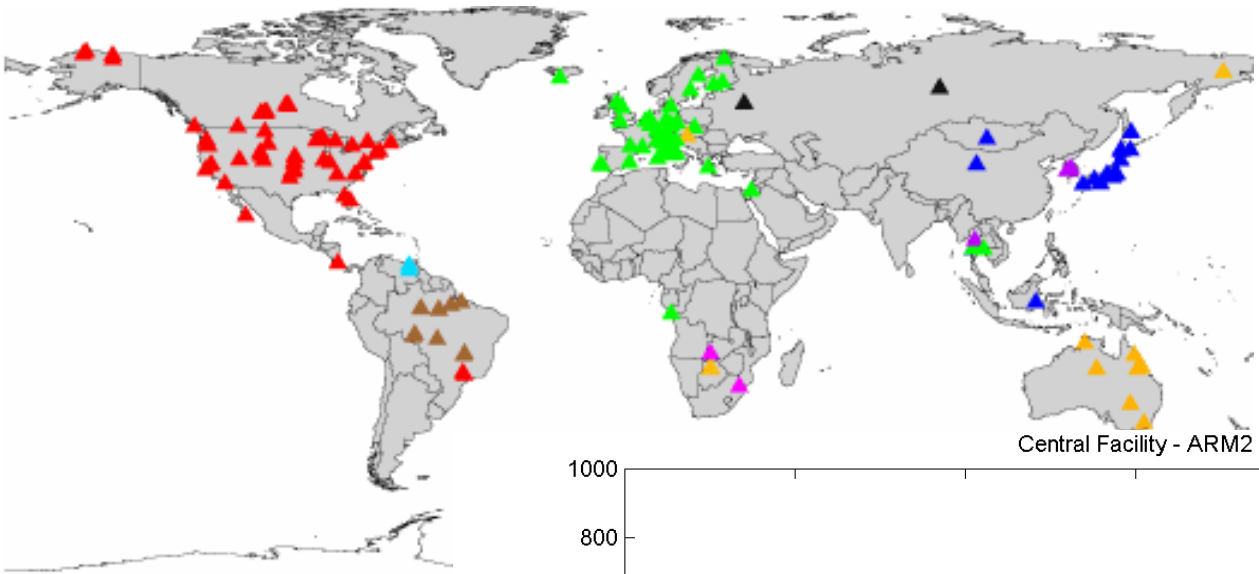
5. Fluxes that have most dramatically changed already in response to human activity.



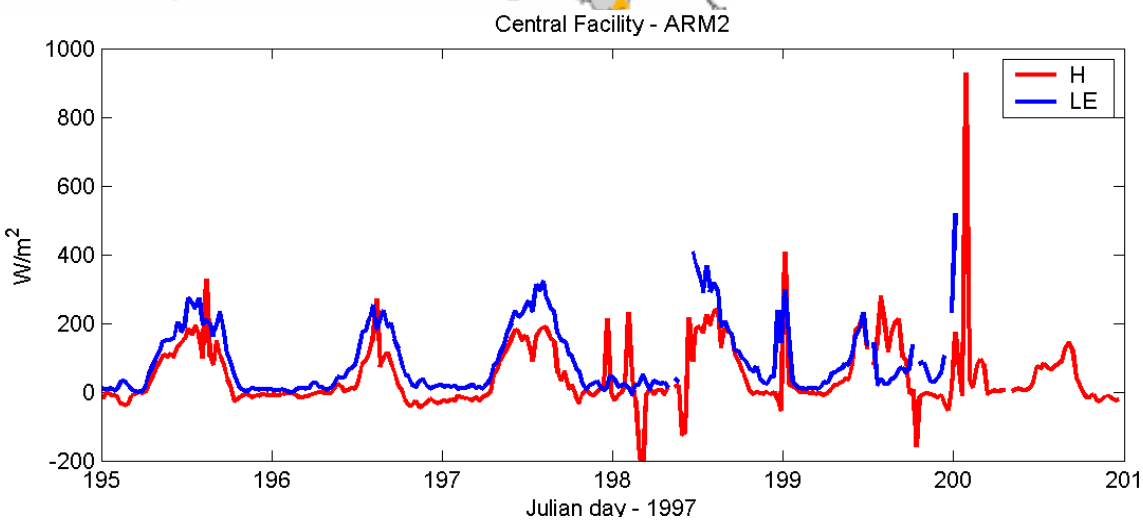
Ocean and Land Evaporation

in situ Networks Inadequate

Even climatology is unknown.



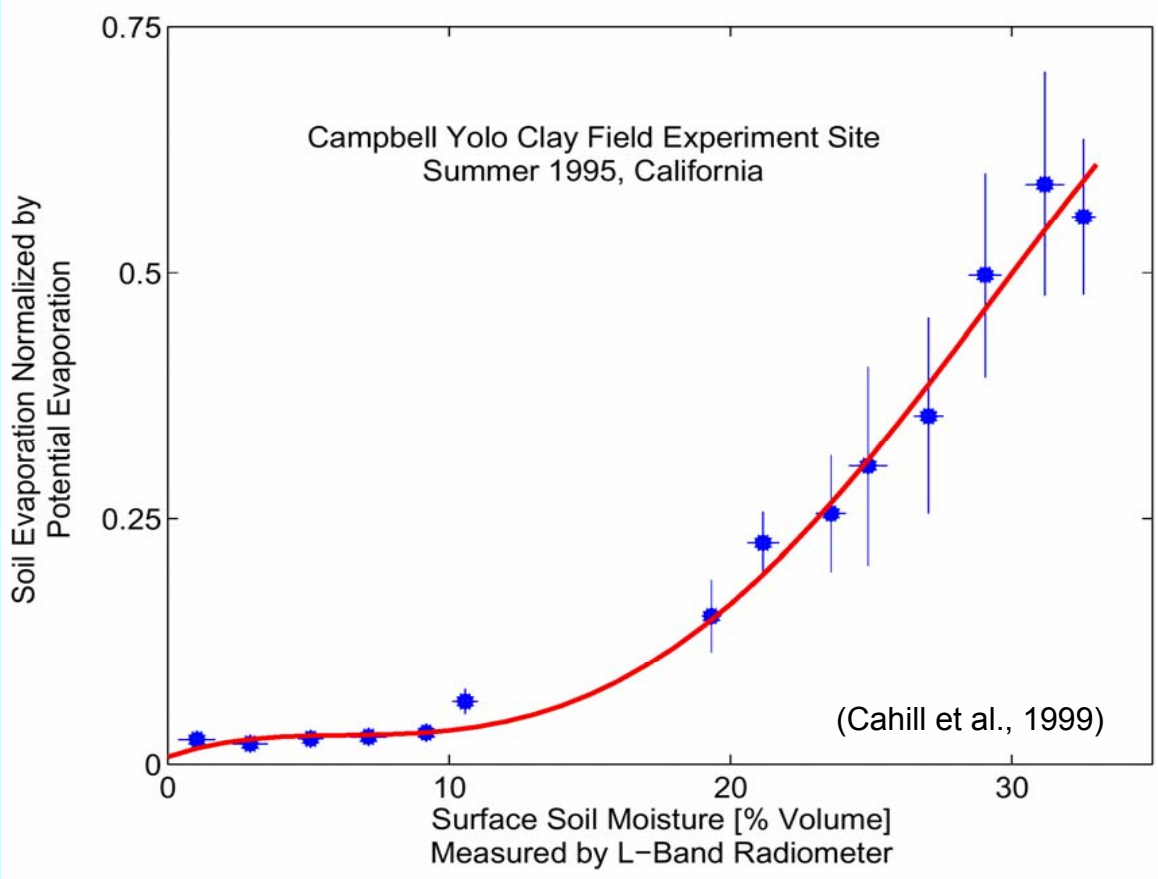
FluxNet, *AmeriFlux*, etc. tower networks



SOA is Primitive:

1. Residual
2. Simulation w/Forcing
3. Crude Closures

Key Closure For Water and Energy Balance



All Models of Water and Energy Balance (Land Surface Models) Include (Explicitly or Implicitly) a Form for the Closure:

e.g., $\beta(\theta)=E/Ep$ or $r_g(\theta)$ …

NOAH

model grid cell and

$$\beta = \left(\frac{\Theta_1 - \Theta_w}{\Theta_{\text{ref}} - \Theta_w} \right)^f \qquad (7)$$

represents a normalized soil moisture availability term where Θ_w is the wilting point and Θ_{ref} is the field capac-

$$F_4 = \sum_{i=1}^{n} \frac{(\Theta_i - \Theta_w) d_{z_i}}{(\Theta_{\text{ref}} - \Theta_w) \left(\sum_{j=1}^{n} d_{z_j} \right)},$$

CLM

functional type and the soil water potential of each soil layer

$$\beta_t = \sum_i w_i r_i \geq 1 \times 10^{-10} \qquad (8.10)$$

where w_i is a soil dryness or plant wilting factor for layer i, and r_i is the fraction of roots in layer i.

The plant wilting factor w_i is

$$w_i = \begin{cases} \dfrac{\psi_{\max} - \psi_i}{\psi_{\max} + \psi_{sat,i}} & \text{for } T_i > T_f \\ 0 & \text{for } T_i \leq T_f \end{cases} \qquad (8.11)$$

"...Let the rate of loss of water from a leaf be denoted by T, then

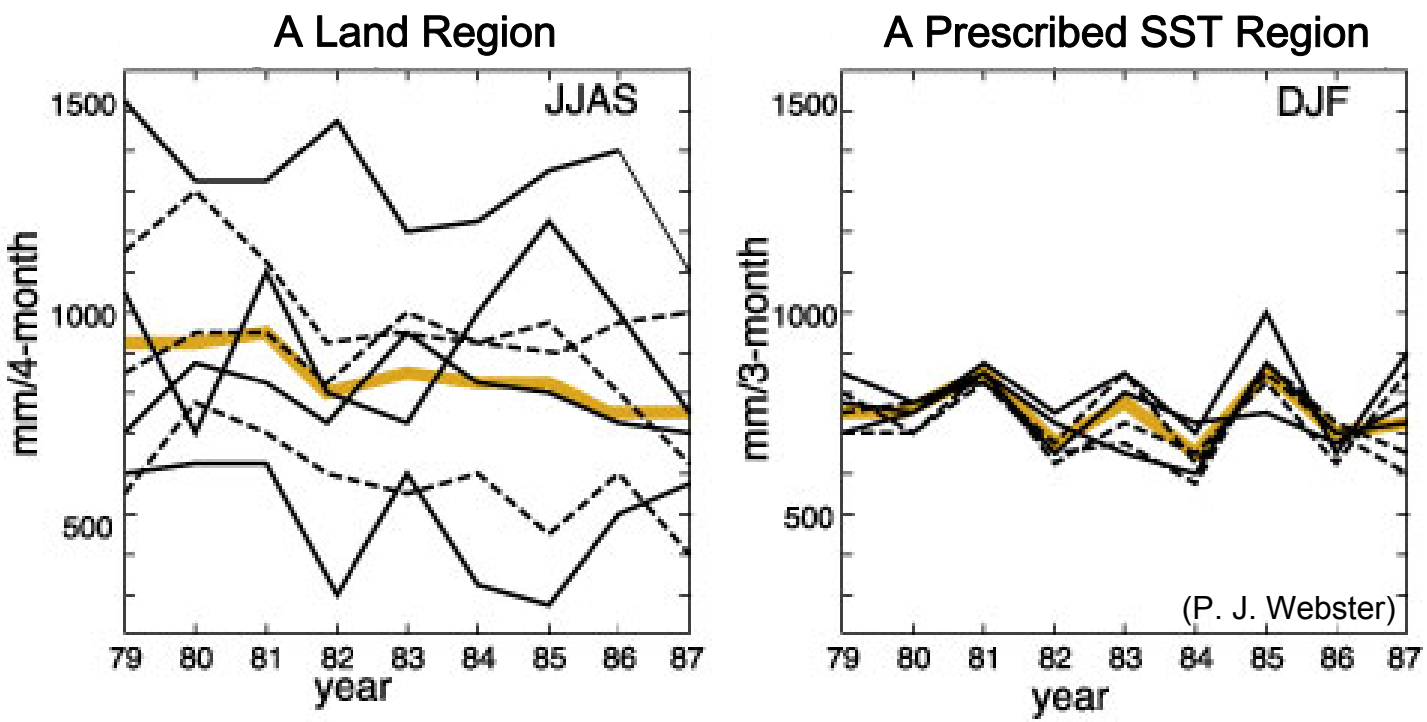
$$T = K\{F(\theta_{leaf}) - w_{air}\}$$

here K is the conductance of the stomatal openings and $F(\theta_{leaf})$ is the saturated vapour density at θ." [*Richardson*, 1922].

Surface Flux

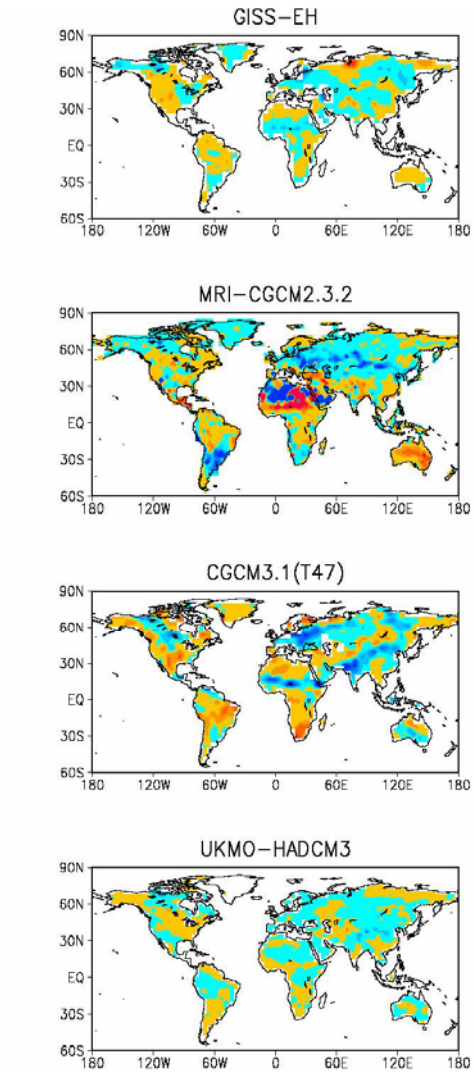
What Happens When We do Not Know BC?

AMIP:

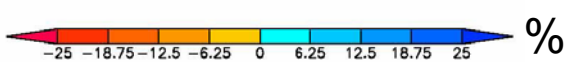


Persistent Uncertainties and
Lack of Forecast-Skill

Uncertainty in Climate Projections of Water Cycle Impact

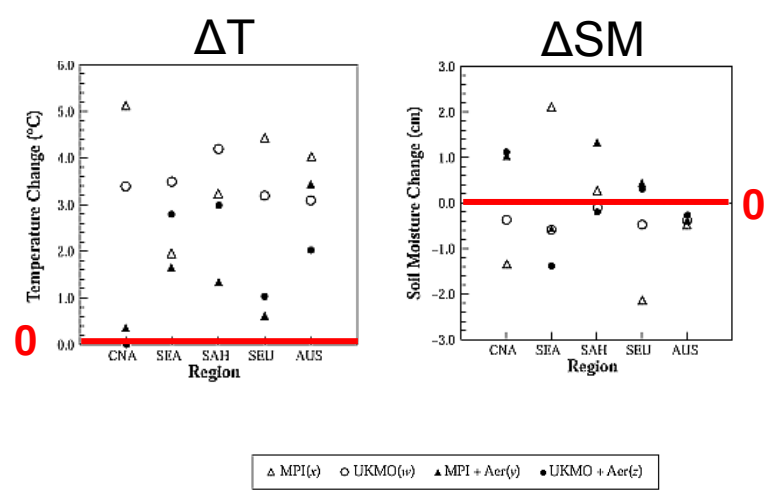


Summer SM – IPCC*



"…models suited for estimating first-order changes in atmospheric temperature profiles…[are] notoriously challenged with regards to reproducing and predicting changes in atmospheric wet processes…"

GEWEX News, 11(1)



cf. Schlosser et al.
*Not Current IPCC

Ocean and Land Evaporation:

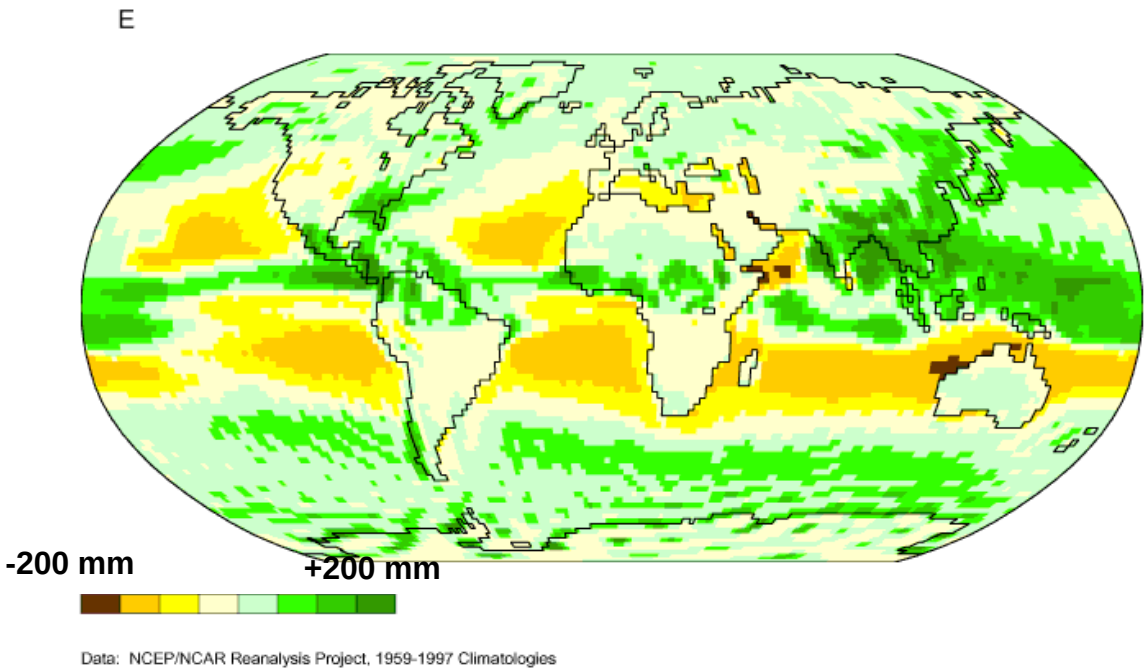
Role of Space-Borne Measurements

Simultaneity of Purposeful Measurements

1. High-Resolution Ocean Vector Winds
2. GEO Microwave Imagers and Sounders
3. L- and P-Band Radar-Radiometers

Milestone in Global Water Cycle Science:

Global **P – E**



Independent Constraints:

1. Ocean Salinity (Follow-On Salinity: SMOS and Aquarius)
2. Land Water Bodies and River Levels (SWOT)
3. Vapor Divergence Tropospheric 3-D Winds and Hi-Res Humidity (Lidar)
4. Atmospheric CO2 (OCO+, GoSat+)
5. Isotopic Ratios (TESS+)
6. High-Resolution Gravimetry (GRACE+)

Recharge:

Currently totally unobserved/unknown.

CO_2 Flux on par with Ocean Sink (0.2 Gt/yr)

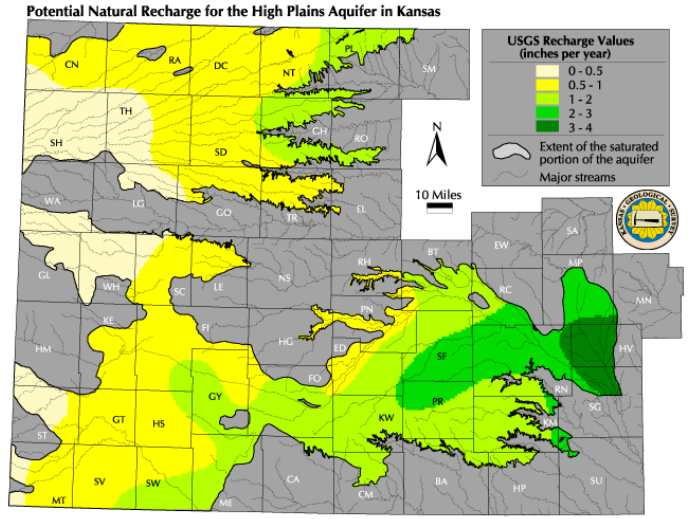
Effective Geochemical Signatures.

Key to Sustainable Resource Use.

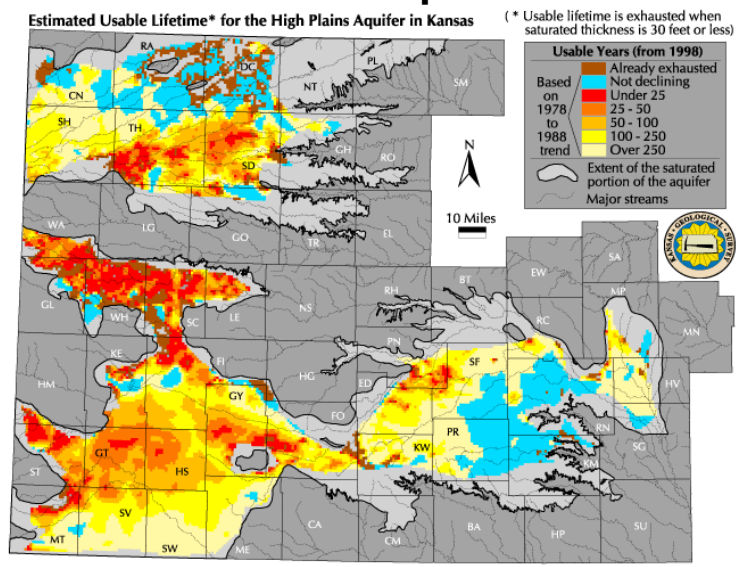
Link to Fine-Scale Topography is Strong.

Soil Moisture Profile Needs to be Known.

Potential Recharge



Time-to-Depletion

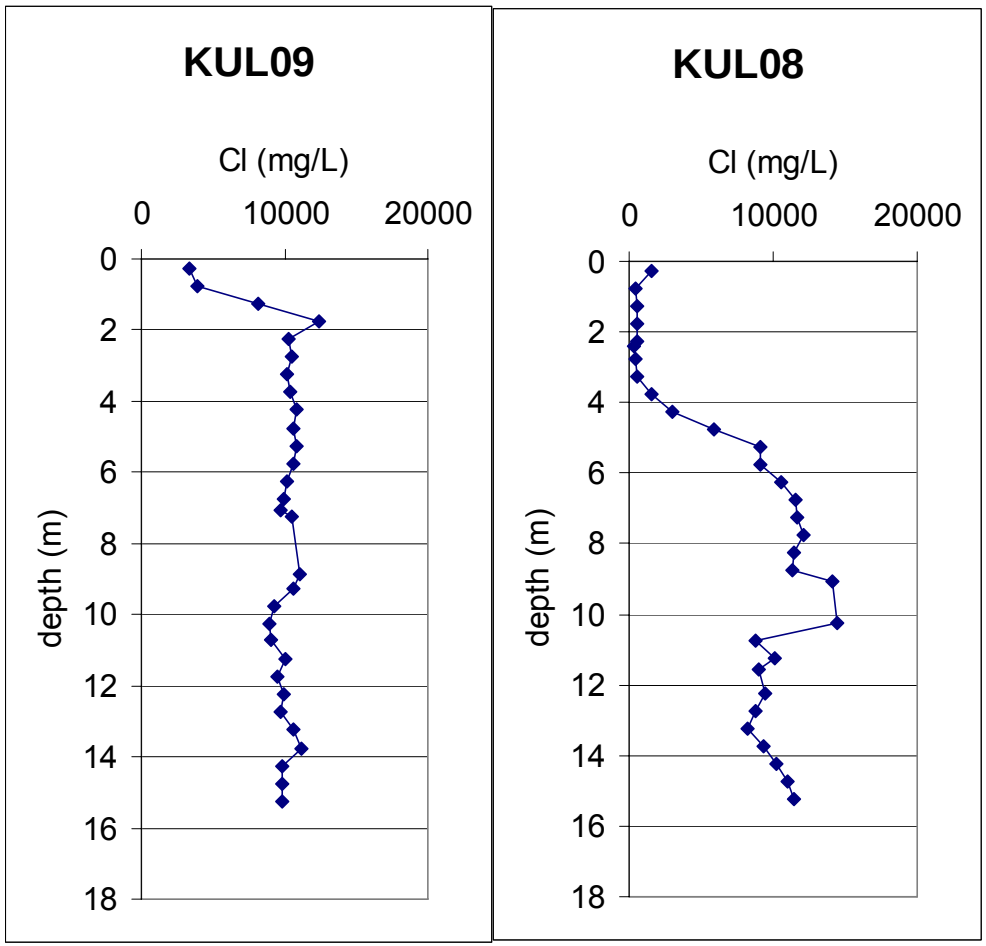


Landuse Change Has Already Significantly Changed This Water Cycle Flux

Recharge:

An Example of Human Impact

Kulkami (Australia)



Undisturbed

Trees-clearing 9 years ago

From 0% to ~30% of Annual Rainfall

Recharge: Role of Space-Borne Observations

1. Simultaneous P- and L-band radar for profile soil moisture (SMAP, MOSS)
2. High-Res Gravity Anomaly for Columnar Water Storage (GRACE+)
3. Lidar for High-Resolution Topgography (LIST)
4. Isotope Measurements (TESS+)

Humans as a Principal Agent

The New Geochemical Cycle…

- Has led to Demise of Ecosystems
- Impacts of Atmospheric Deposition Unknown

Global sources of biologically-available N

Sources	N Release (Tg)
Fertilizer	80
Crops	40
Fossil fuels and biomass burns	60
Land-use change	30
Total from human sources	**210**
Natural sources	**140**
(bacteria, lightning)	

Vitousek et al., "Human Alteration of the Global Nitrogen Cycle: Causes and Consequences," Issues in Ecology, No. 1 (1997), pp. 4-6.

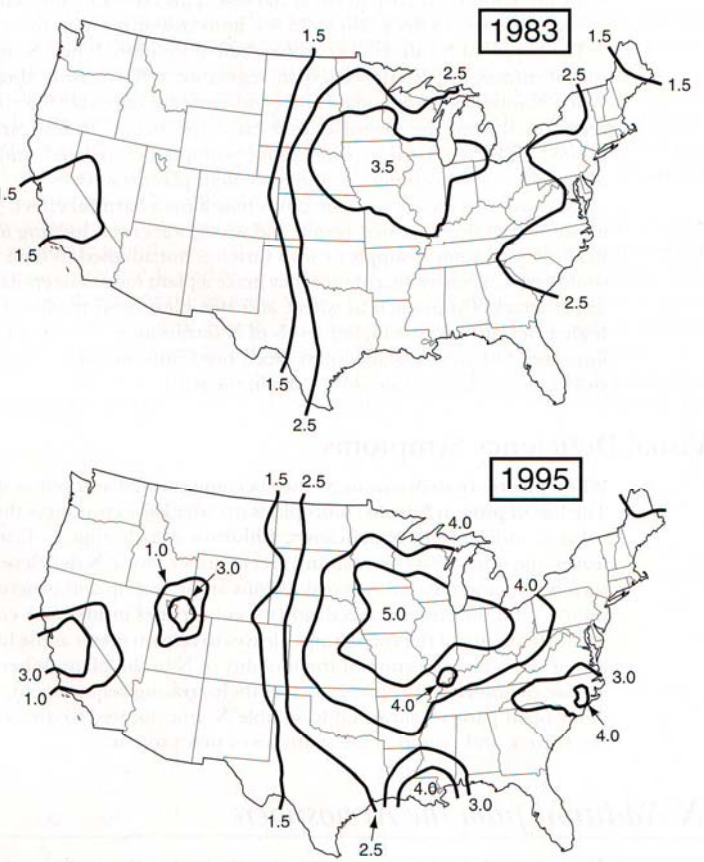


FIGURE 4.3 Spatial distribution of NH_4^+ (kg/ha) deposited in 1983 and 1995 illustrates increasing trend in N deposition. *National Atmospheric Deposition Program, 1996.*

Heterogeneous Processes

A Primary Source of Uncertainty in Water Cycle Science

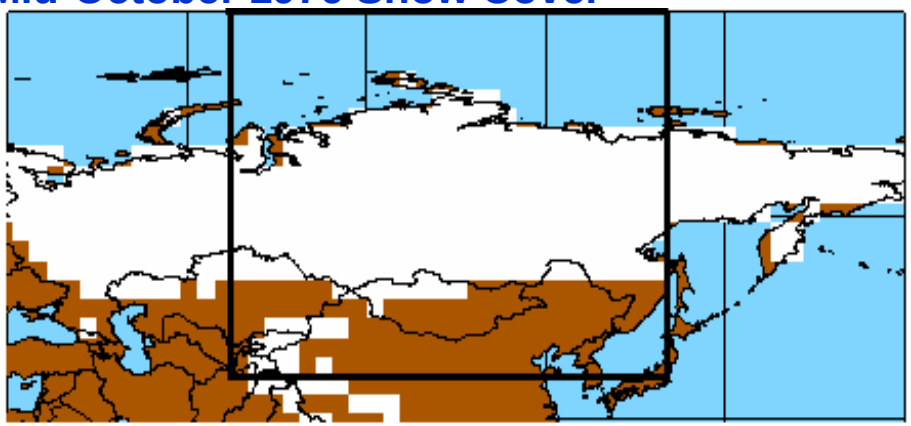
Aerosol-Precipitation Microphysics and Chemistry

Measurements:

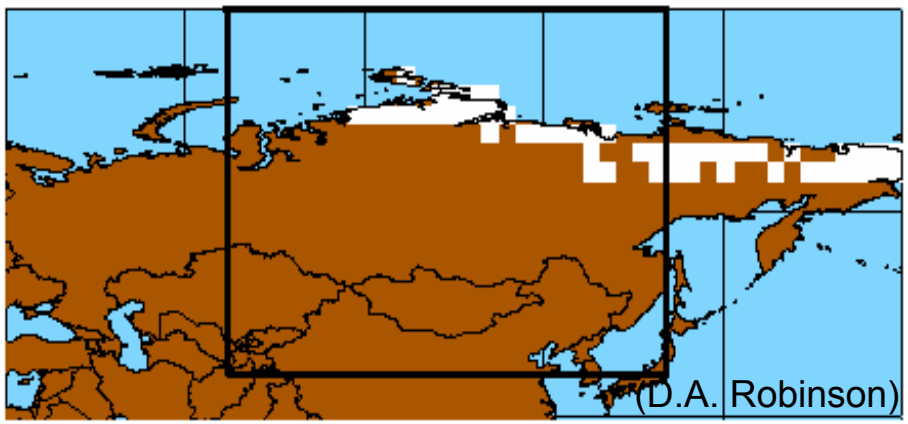
- High Spectral Resolution Lidar for Aerosol Detection
- Multi-Frequency Doppler Radar for Cloud Content and Vertical Motions
- Advanced Lidar for Tropospheric Winds

Heterogeneous Processes: Snow

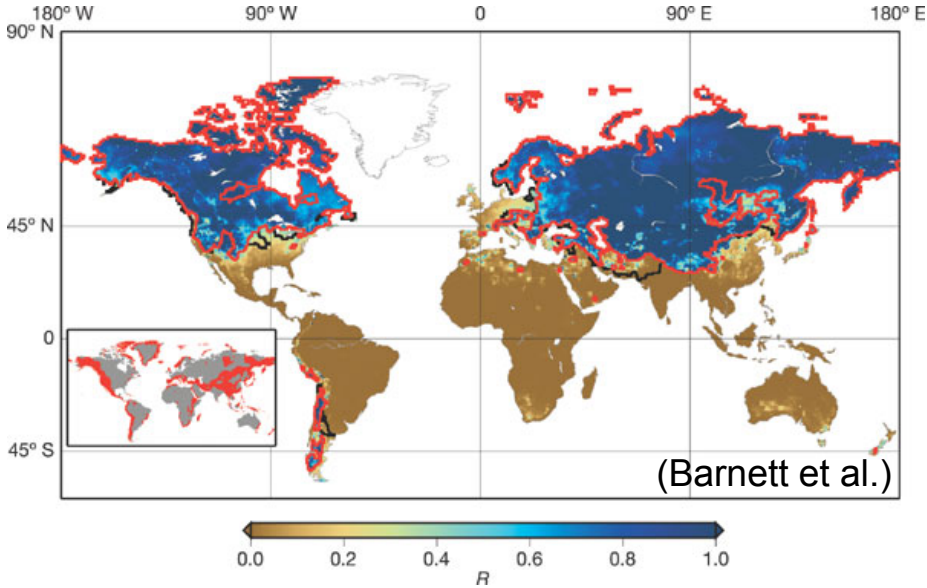
Mid-October 1976 Snow Cover



Mid-October 1988 Snow Extent

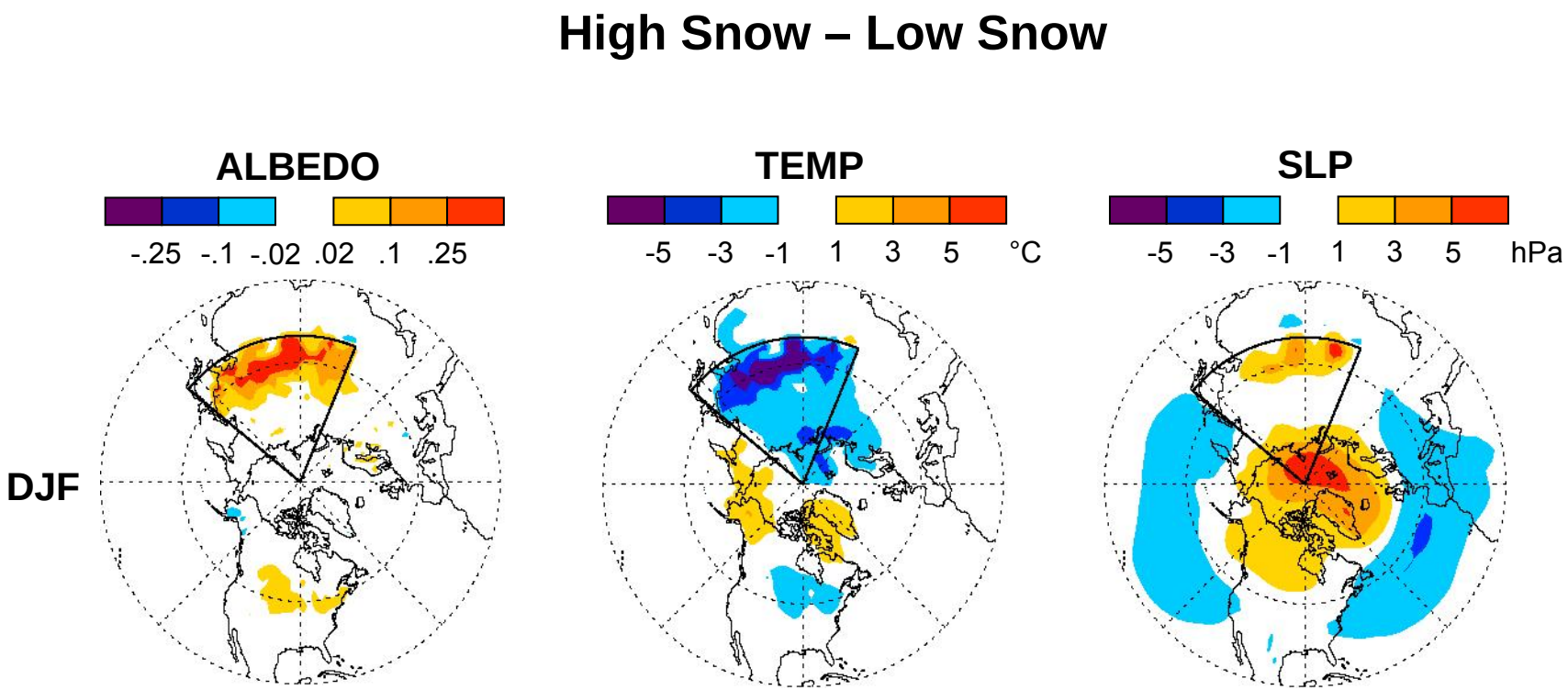


1. Precipitation
2. Drift
3. Packing and Melting



Regions Where Available Water is Snowmelt-Dominated

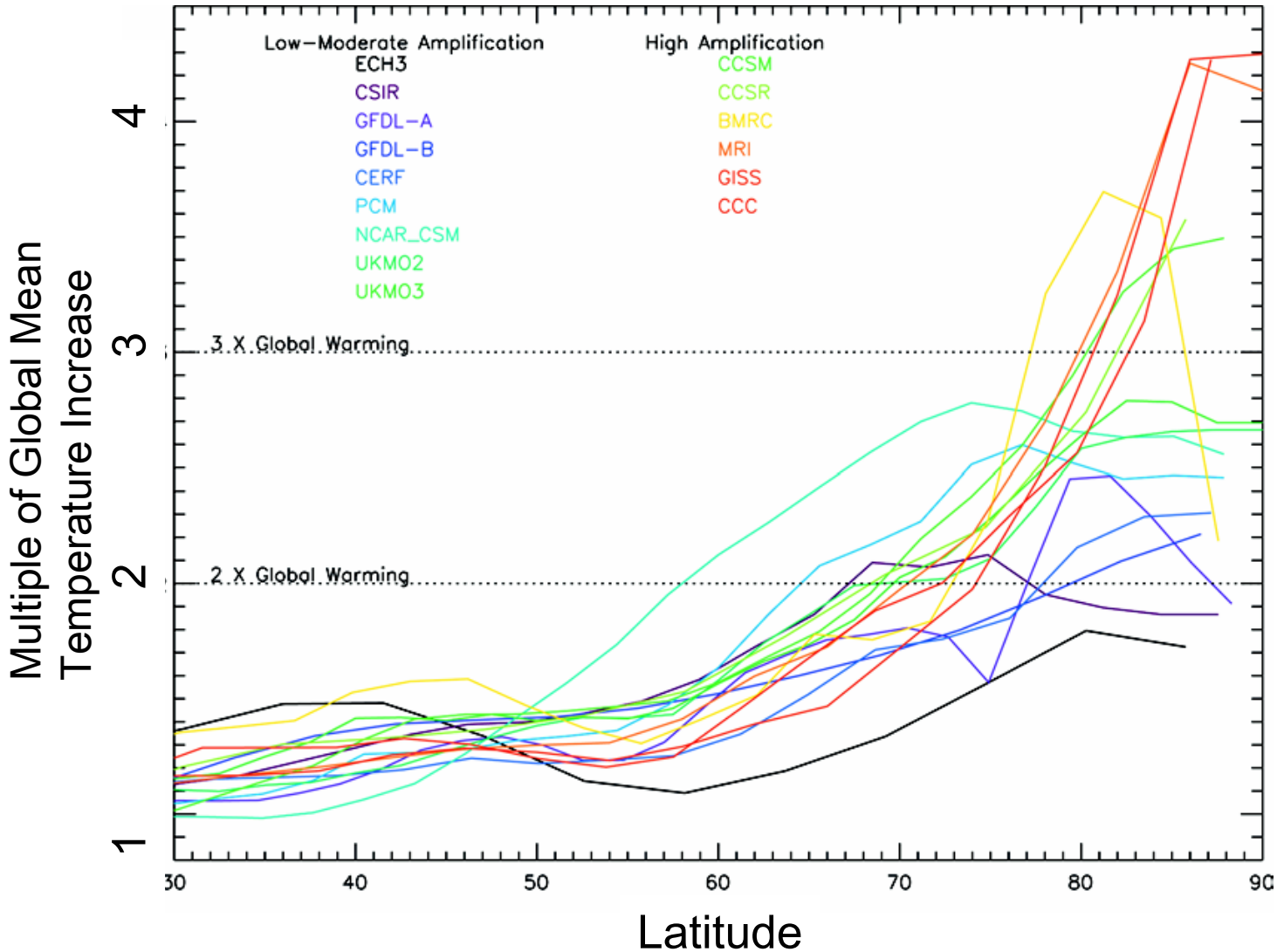
Diabatic Heating Anomalies Due to Snow and Sea-Ice Have Global Effects



Observed positive snow forcing over Siberia results in modeled negative AO mode climatic response. ~30% of total AO mode variability

Polar Amplification

Common Scenario:
+1% yr^{-1} CO_2



Potential for:

1. Abrupt Climate Change
2. Significant Methane Release

Holland et al., 2003:
Clim Dyn. 21(3)

SPACE NEWS
February 19, 2007

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1. Is Earth science just another disciplinary specialty?

2. Do we monitor the environment for our amusement?

Earth Science Decadal Survey

The Process:

100+ Mission Concepts Submitted by Community

Prioritized List By Report Concludes With **17** Missions:

- 14 NASA
- 2 NOAA
- 1 Joint

TABLE ES.2 Launch, orbit, and instrument specifications for the recommended NASA missions. Shade colors denote mission cost categories as estimated by the NRC ESAS committee. Pink, green, and blue shadings represent large ($600 million to $900), medium ($300 million to $600 million), and small (<$300 million) missions, respectively. Missions are listed in order of ascending cost within each launch timeframe. Detailed descriptions of the missions are given in Part II, and Part III provides the foundation for selection.

Decadal Survey Mission	Mission Description	Orbit	Instruments	Rough Cost Estimate
Timeframe 2010 – 2013, Missions listed by cost				
CLARREO (NASA portion)	Solar radiation: spectrally resolved forcing and response of the climate system	LEO, Precessing	Absolute, spectrally-resolved interferometer	$200 M
SMAP	Soil moisture and freeze/thaw for weather and water cycle processes	LEO, SSO	L-band radar L-band radiometer	$300 M
ICESat-II	Ice sheet height changes for climate change diagnosis	LEO, Non-SSO	Laser altimeter	$300 M
DESDynI	Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	LEO, SSO	L-band InSAR Laser altimeter	$700 M
Timeframe: 2013 – 2016, Missions listed by cost				
HyspIRI	Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health	LEO, SSO	Hyperspectral spectrometer	$300 M
ASCENDS	Day/night, all-latitude, all-season CO_2 column integrals for climate emissions	LEO, SSO	Multifrequency laser	$400 M
SWOT	Ocean, lake, and river water levels for ocean and inland water dynamics	LEO, SSO	Ka-band wide swath radar C-band radar	$450 M
GEO-CAPE	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	GEO	High and low spatial resolution hyperspectral imagers	$550 M
ACE	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry	LEO, SSO	Backscatter lidar Multiangle polarimeter Doppler radar	$800 M
Timeframe: 2016 -2020, Missions listed by cost				
LIST	Land surface topography for landslide hazards and water runoff	LEO, SSO	Laser altimeter	$300 M
PATH	High frequency, all-weather temperature and humidity soundings for weather forecasting and SST[a]	GEO	MW array spectrometer	$450 M
GRACE-II	High temporal resolution gravity fields for tracking large-scale water movement	LEO, SSO	Microwave or laser ranging system	$450 M
SCLP	Snow accumulation for fresh water availability	LEO, SSO	Ku and X-band radars K and Ka-band radiometers	$500 M
GACM	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	LEO, SSO	UV spectrometer IR spectrometer Microwave limb sounder	$600 M
3D-Winds (Demo)	Tropospheric winds for weather forecasting and pollution transport	LEO, SSO	Doppler lidar	$650 M

[a] Cloud-independent, high temporal resolution, lower accuracy SST to complement, not replace, global operational high accuracy SST measurement.

Decline of Observing System

Science and Applications Follow

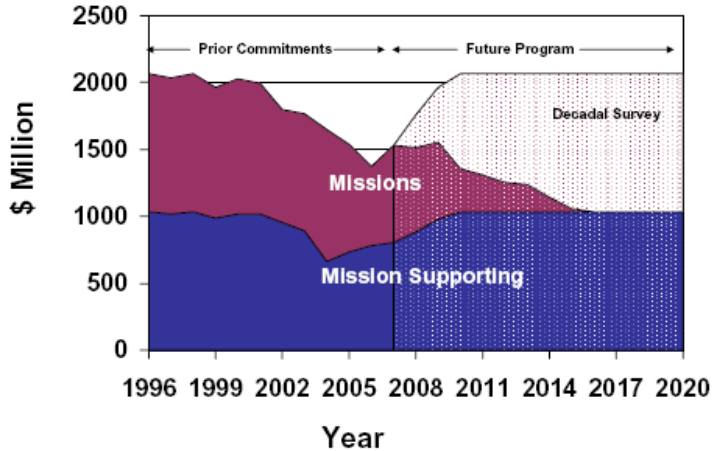


FIGURE 2.7a The NASA budget for Earth Science for the period 1996 to 2020 showing both the decline in funding during the current decade and the increase required to implement the committee's recommendations (in fixed FY2006 dollars). The white dotted areas represent future commitments to ongoing missions and research and analysis efforts. The red dotted "Decadal Survey" area represents the budget wedge that would support the Committee's recommendations regarding missions and technology development in the next decade.

- Restore to Level of Decade Ago

Conclusion

Water Cycle Ramifications of Global Change Are Unknown in <u>Sign</u>.

Global Change: - Landuse Conversions That Has Already Happened
- Enhanced Greenhouse Effect

We Are Macro-Engineering the Earth Without Knowing First-Order Impacts.

Transformational Satellite Observations to Gain Certainty:

1. Aerosols-Precipitation Efficiency
2. Surface Control on Evaporation
3. Recharge (Mass and Geochemical Rates)
4. Freeze/Thaw and Snowpacks (Polar Amplification)
5. …

Action Needed

Earth Science is in an Existential Struggle.

1. Disciplinary Response is Helpful But Not Sufficient

2. Substantively Support Anthes/Moore in House Efforts.

3. Form a Water Cycle/Water Resources Delegation to Target Key House Committees/Staffers. Influence/Induce Hearings.

4. Delegation: Concise Science and Applications Voices, Former Centers Developers, Universities DC Reps, +.

Backup Slides

Major Technological Development: Commonalities

- Large Light-Weight Deployable Mesh Antennas for Multi-Frequency Microwave

  Land States (θ, T) and Ocean Surface Conditions (SST, S, U)

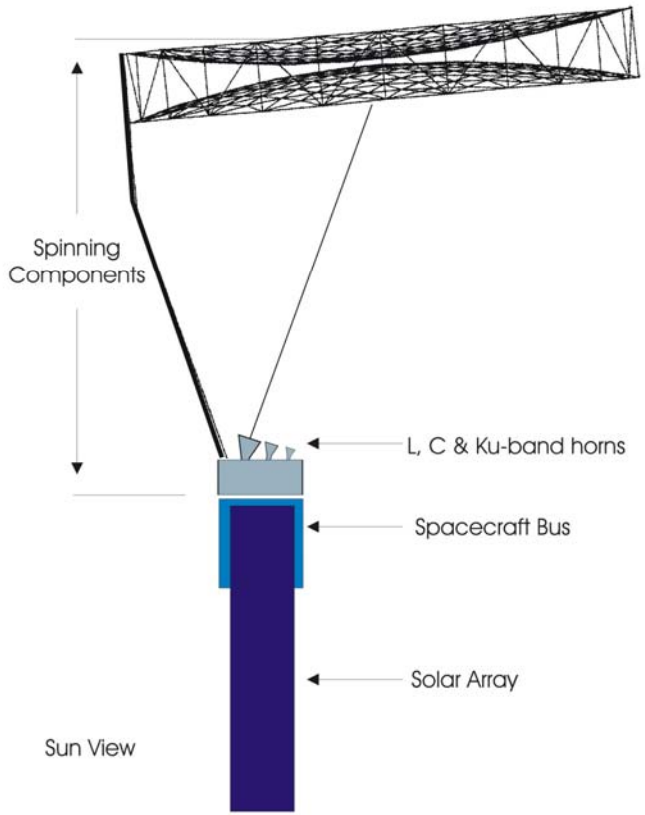
SMAP	**L-Band Radar and Radiometer**
MOSS	**P-Band Radar and Radiometer**
SCLP	**X- and Ku-band Radar and K- and Ka-Band Radiometer**
WOWS	**Ku-Band Radar and K- and X-Band Radiometer**

- MEO and GEO Microwave Imaging and Sounding (Water Vapor Convergence)
- Wide-Swath Altimetry (Water and River Elevation; Ice Bodies)
- Advanced Lidar (3-D Winds and Accurate Topography)
- Chemical Sensing (Hi-Res CO2, Isotopes)
- Hyperspectral Imaging (Water Quality, Vegetation Differentiation)

Technological Commonalities For Water Cycle Mission

SMAP	**L-Band Radar and Radiometer**
MOSS	**P-Band Radar and Radiometer**
SCLP	**X- and Ku-band Radar and K- and Ka-Band Radiometer**
WOWS	**C- and Ku-Band Radar and C-, K- and X-Band Radiometer**

1. GPM Follow-On
2. Ocean Wind
3. Soil Moisture Profile
4. Land Freeze/Thaw
5. Cold-Land Processes
6. Biomass Monitoring
7. Precipitable Water
8. SST and LST
7. SSS Follow-On



Measurement Priorities of Water Cycle Panel

1. Soil Moisture and Freeze/Thaw (SMAP, MOSS)
2. Surface Water and Ocean Topography (SWOT)
3. Snow and Cold Land Processes (SCLP)
4. Water Vapor Transport (AIRS, GPS RO, WOWS)
5. Sea Ice Thickness, Glacier Surface Elevation, Glacier Velocity (ICESAT+ and InSAR)
6. Groundwater Storage, Ice Sheet Mass Balance and Ocean Mass (GRACE II, ICESat+)
7. Inland Water Quality (FLORA, SAVII)

Surface:

Ground heat flux ?

$$R_n - G = H + LE$$

Static approach

$$G = c \cdot R_n$$ (e.g. SEBAL, ALEXIS,…)

$$c \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial t^2}$$

$$G = -\kappa \frac{\partial T}{\partial z}$$

Dynamic approach

System Equation

Surface Medium Heat Diffusion:

$$\frac{dT_s}{dt} = -2\sqrt{\pi\omega}\,\frac{L \cdot E_s + H_s - R_n}{P_s} - 2\pi\omega\left(T_s - T_{deep}\right)$$

$$\boxed{EF} = \frac{L\ E_s}{H + L\ E}$$

Evaporative Fraction

Constant During Daytime

$$H = \rho c_p \boxed{C_{H_{CS}}}\left(T_{surf} - T_{air}\right)U$$

$$L \cdot E = \rho L \boxed{C_{H_{CS}}}\left(q_{surf} - q_{air}\right)U$$

Constant During Month

Uses No Information About Land Cover and Vegetation

Variational Adjoint-State Assimilation System

Minimize a Multi-Scale Penalty Function:

Remote Sensing

$$J = \left[\mathbf{T_{obs}} - \overline{\mathbf{M}} \cdot \mathbf{T}_R\right]^T \overline{\mathbf{G}}_{Ts}^{-1} \left[\mathbf{T_{obs}} - \overline{\mathbf{M}} \cdot \mathbf{T}_R\right] +$$

State Misfit Penalty

$$+ \left[\mathbf{EF} - \mathbf{EF'}\right]^T \overline{\mathbf{G}}_{EF}^{-1} \left[\mathbf{EF} - \mathbf{EF'}\right] +$$

$$+ \left[\mathbf{C}_H - \mathbf{C}_H'\right]^T \overline{\mathbf{G}}_{CB}^{-1} \left[\mathbf{C}_H - \mathbf{C}_H'\right] +$$

Parameter Estimation Error Penalty

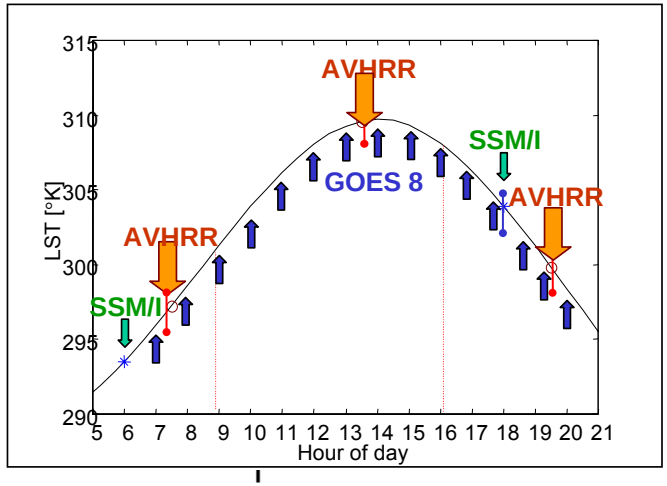
$$+ \int_{\upsilon} \mathbf{\Lambda}^T \left[\frac{d\mathbf{T_s}}{dt} - F\left(\mathbf{T_s}, \mathbf{EF}, \mathbf{C}_{HS}\right)\right] dt$$

Adjoint Physical Model

EF varies daily, C_h vary on a monthly time scale

Example of assimilation of multi-scale/multi-sensor LST estimates (SGP '97)

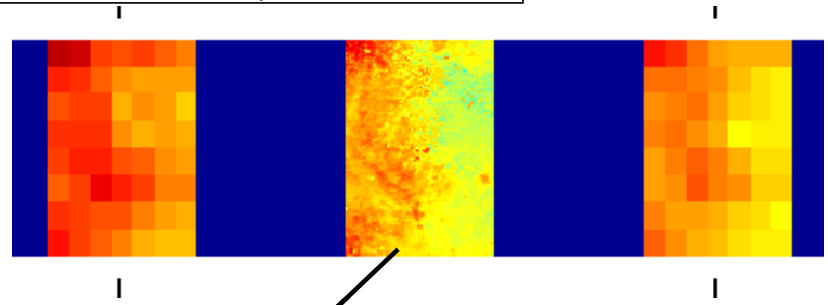
LST retrieval scales:
~ 50 x 50 km – GOES 8
~ 20 x 20 km – SSM/I
~ 1 x 1 km - AVHRR

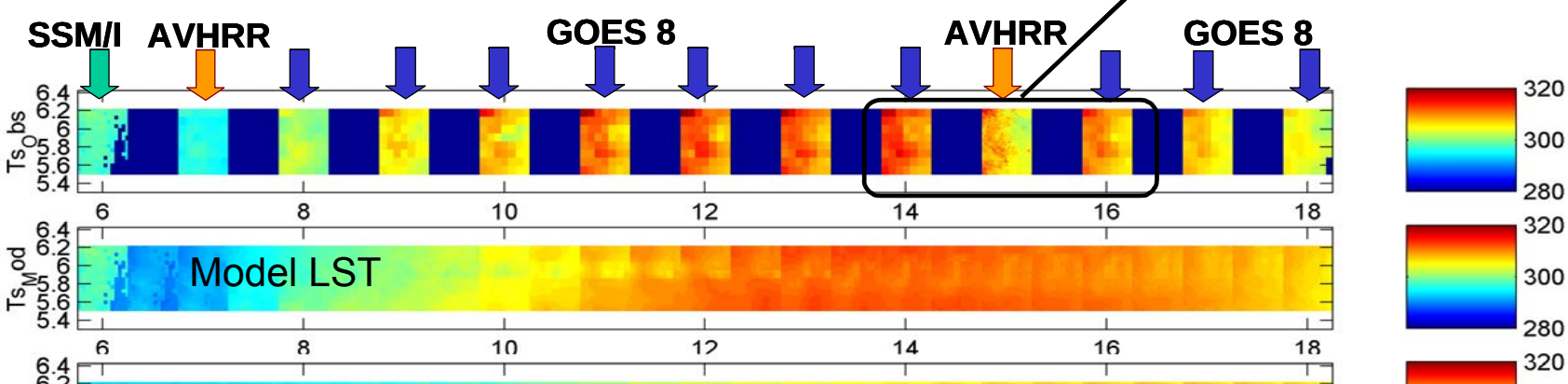


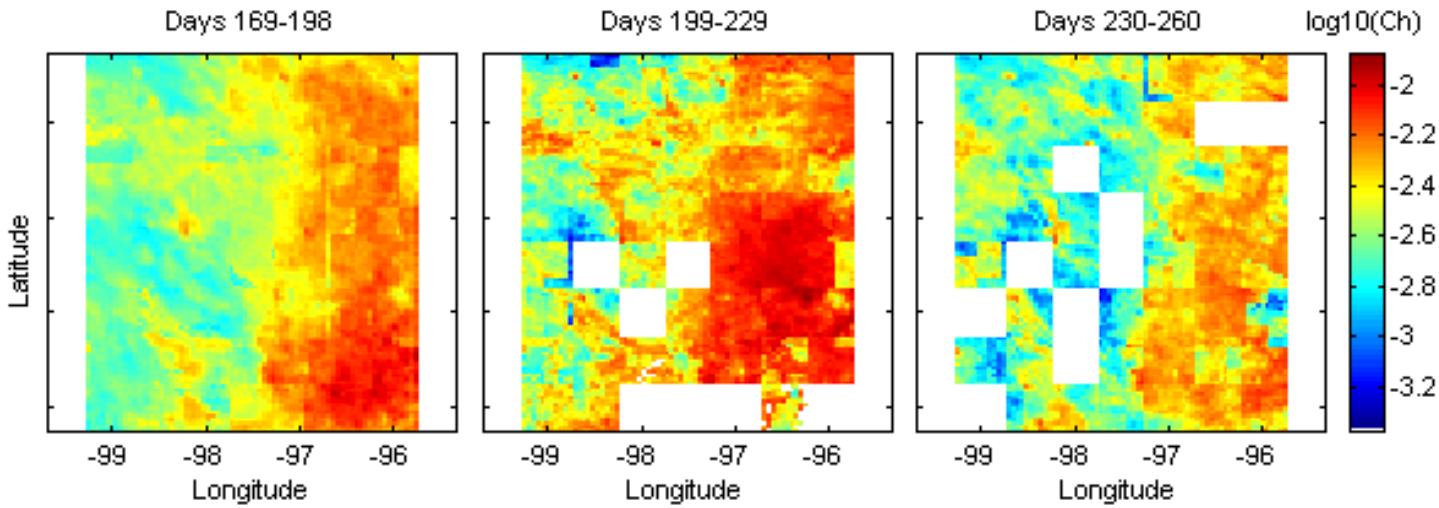
Model state scale:
4 x 4 km

Assimilation in 3 sub-periods (30 days each) June 18th - September 17th, 1997

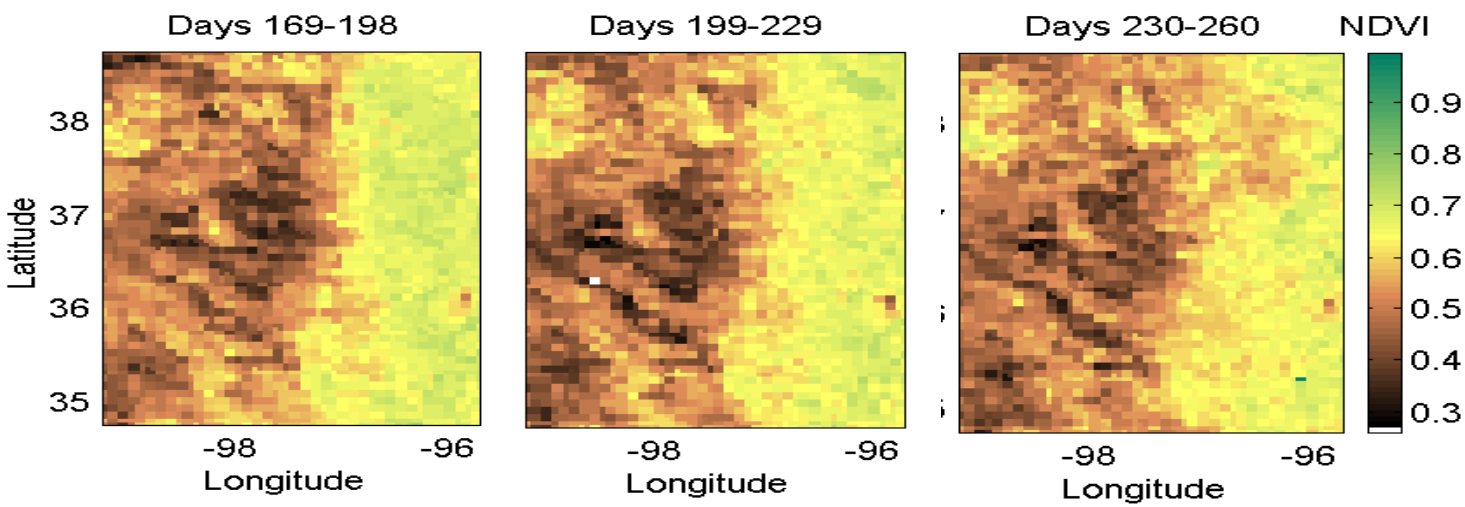
Daily set-up of LST assimilation at ½ hour time resolution





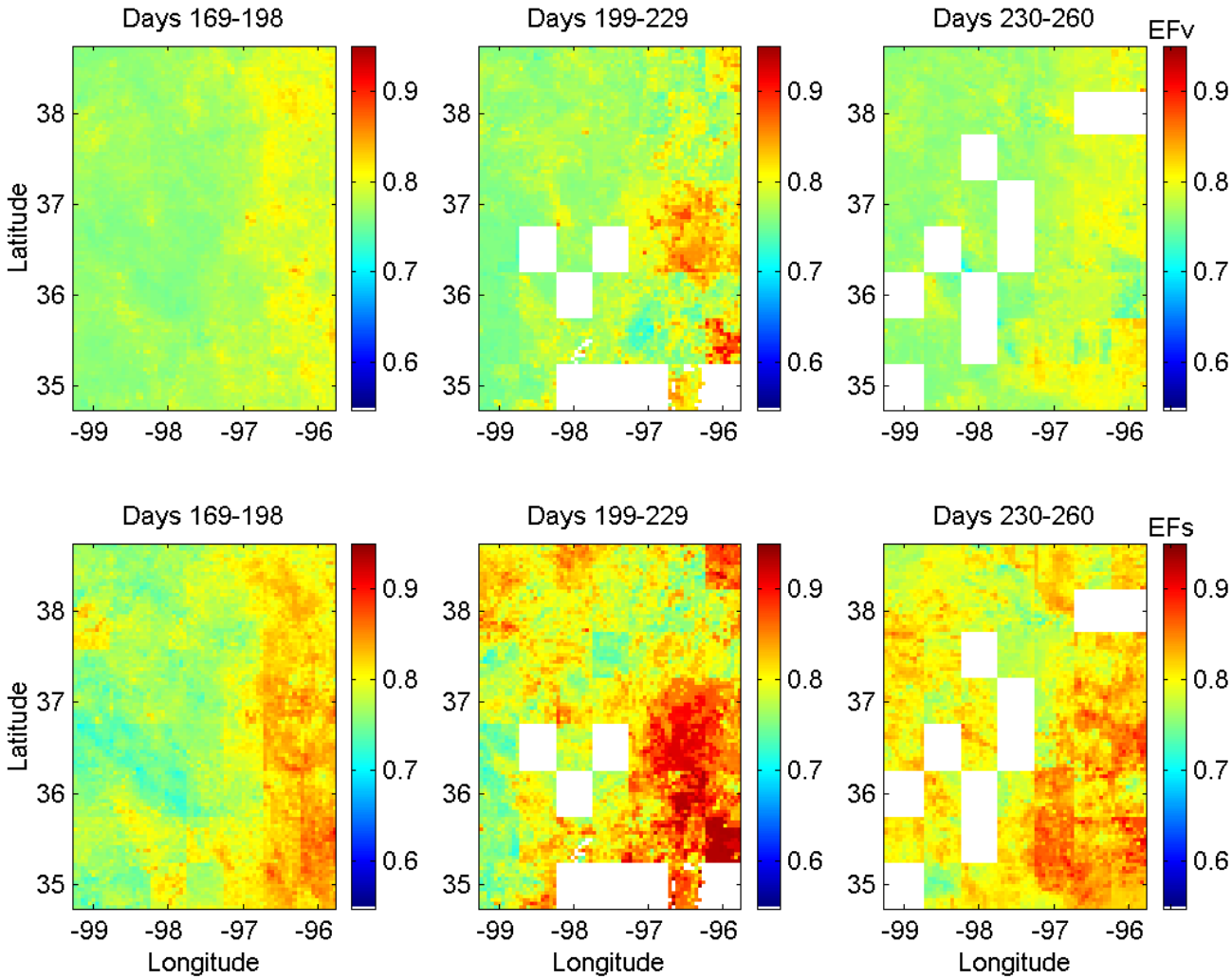


C_h



NDVI

(Not Used)


Days 169-198
Days 199-229
Days 230-260
EFv
EFs
Latitude
Longitude
38
37
36
35
-99
-98
-97
-96
0.9
0.8
0.7
0.6

EF_v

EF_s