The MODIS Energy Balance Product Suite

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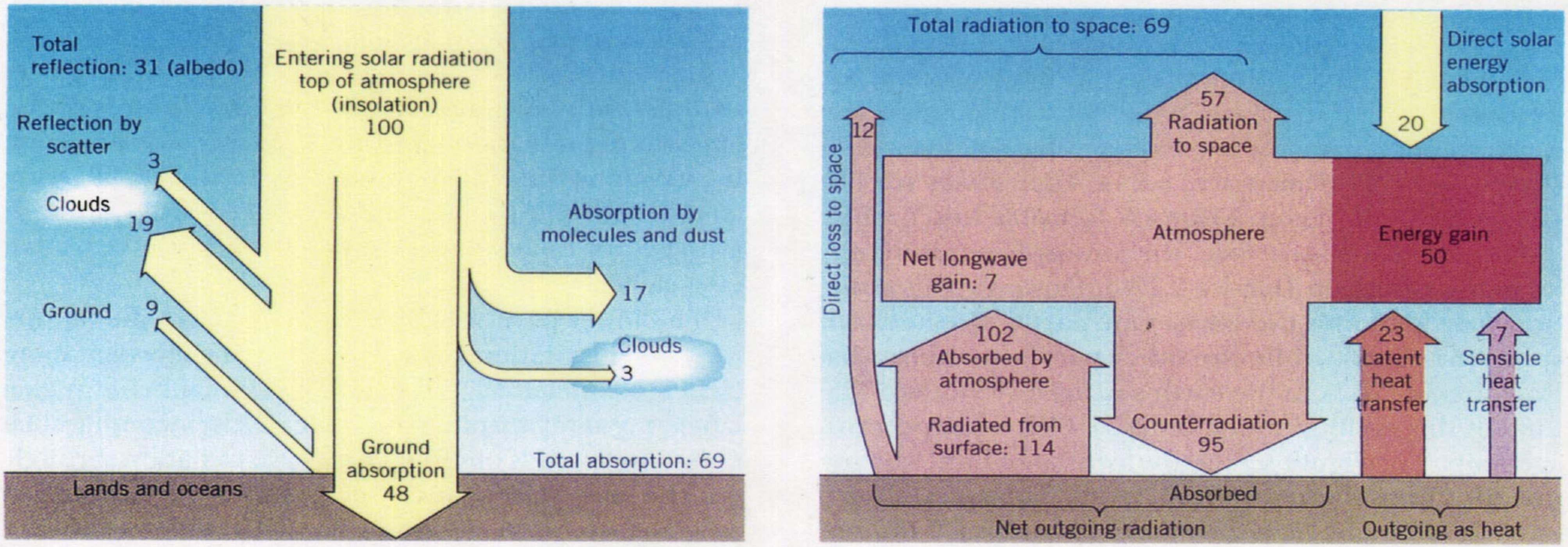
Global Change and Earth's Radiation Budget

- Understanding and monitoring global change requires a global viewpoint that can only come consistently from satellite observations
- Climate and hydrologic systems are highest among global change science priorities in EOS
  - Includes measurements of land / atmosphere / ocean energy and water fluxes for surface energy and mass balances
- Understanding and modeling global climate change requires monitoring the spatial and temporal variations of the earth's radiation budget
  - Top-down: Global Energy Balance
  - Bottom-up: Surface Energy Balance

Global Energy Balance

- Key Shortwave Fluxes
  - Planetary albedo: cloud and surface reflectance (31%)
  - Absorption: atmosphere and surface (69%)
- Key Longwave Fluxes
  - Atmosphere: Up- and downwelling emittance
  - Surface: Net longwave radiation to sky (19%)
- Heat Transfer
  - Sensible (23%)
  - Latent (7%)
- Role of MODIS Measurements
  - Atmosphere: cloud, water vapor, aerosol characterization
  - Oceans: sea surface temperature
  - Land: surface reflectance, albedo, land surface temperature, snow / ice properties and extent; land surface properties from LAI and land cover type

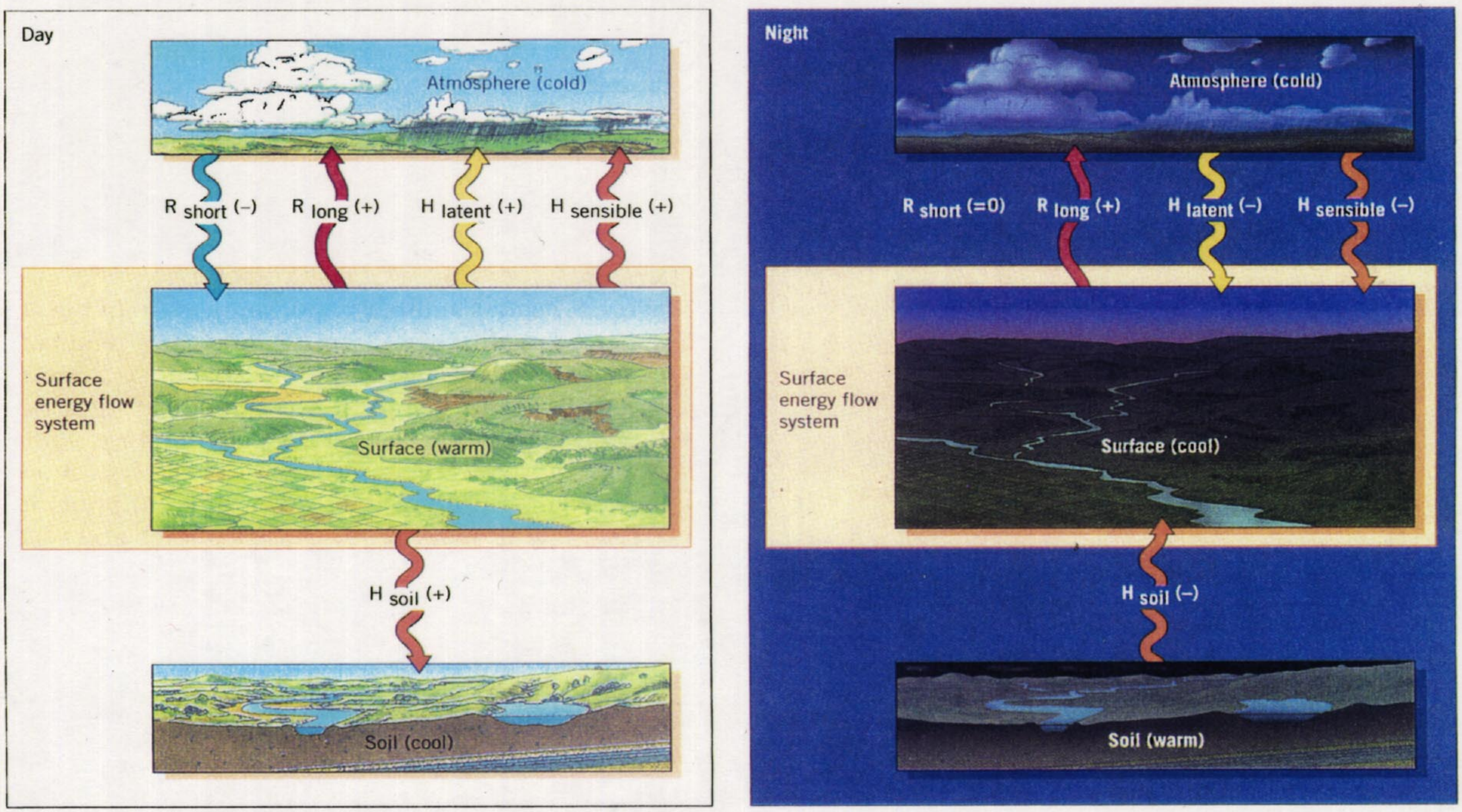
Figure 2.13 Diagram of the global energy balance. Values are percentage units based on total insolation as 100. The left figure shows the fate of incoming solar radiation. The right figure shows longwave energy flows occurring between the surface and atmosphere and space. Also shown are the transfers of latent heat, sensible heat, and direct solar absorption that balance the budget for earth and atmosphere. Data of Kiehl and Trenberth, 1997.



Land Surface Energy Balance

- Land Surface Energy Balance
  - Highly dynamic and spatially variable
  - Temporal and spatial integral gives global energy balance
- Fluxes
  - Shortwave radiation
  - Longwave radiation

  Net radiation
  - Latent, sensible, soil heat fluxes
- Diurnal Variation
  - Day
    - Surface shortwave absorption provides heat fluxes to atmosphere and soil
  - Night
    - Longwave radiation loss balanced by heat fluxes from atmosphere and soil



Diagrams of the surface energy balance equation for typical day and night conditions.

Land Surface Energy Balance, cont.

- Role of MODIS Land Products
  - Daily / nightly mapping of surface parameters that drive the instantaneous land surface energy balance
  - Net radiation:
    - Surface absorption / albedo determined from:
      - Surface reflectance
      - BRDF / Albedo
      - Snow extent
    - Longwave radiation balance determined from:
      - Land surface temperature
  - Latent and sensible heat fluxes
    - Surface resistances parameterized from
      - LAI
      - Land Cover Type

MODIS Land Group Products

- MODLAND Products
  - ***Surface Reflectance (Vermote)***
  - ***Land Surface Temperature (Wan)***
  - ***Snow/Ice Cover (Hall/Salomonson)***
  - Land Cover / Land-Cover Change (Strahler)
  - 250-m Land-Cover Change and Continuous Fields (Townshend)
  - Thermal Anomalies (Justice)
  - Vegetation Indexes (Huete)
  - ***Bidirectional Reflectance/Albedo (Strahler)***
  - Leaf Area Index (LAI) / Fraction of Absorbed Photosynthetically-Active Radiation (FPAR) (Myneni, Running)
  - Photosynthesis / Annual Net Primary Productivity (Running)

Surface Reflectance (MOD09R)

- Objective:
  - Provide reflectance values independent of atmospheric conditions
- Features:
  - Outputs atmospherically-corrected surface bidirectional reflectance
  - Provided for MODIS Land Bands at 250-, 500-m spatial resolutions
  - Aerosol characteristics derived from MODIS aerosol product using “improved” dark target algorithm that provides for variable dark target reflectance
  - Cloud- and cloud-shadow masked
  - Corrected for thin cirrus
  - Corrected for surface BRDF and adjacency effects on multiple scattering (postlaunch)
  - Level 2, 2G, 250- and 500-m resolution depending on band
  - Level 3 minimum-blue 16-day composited product

Surface Reflectance Prototyping

- SeaWiFS Prototyping
  - 8 spectral bands in VNIR
  - Data begin September, 1997
  - Resolution collapsed to 8-km for global processing
  - Minimum-blue monthly composite to select near-nadir, cloud-free, clearest data (but also selects shadows)
- Prototype Studies
  - Spectral plots and mapping of minimum-blue multiband images
  - Retrieval of aerosols based on AVHRR-SeaWiFS fusion
  - Mapping of vegetation indexes—NDVI, EVI—to protype VI products

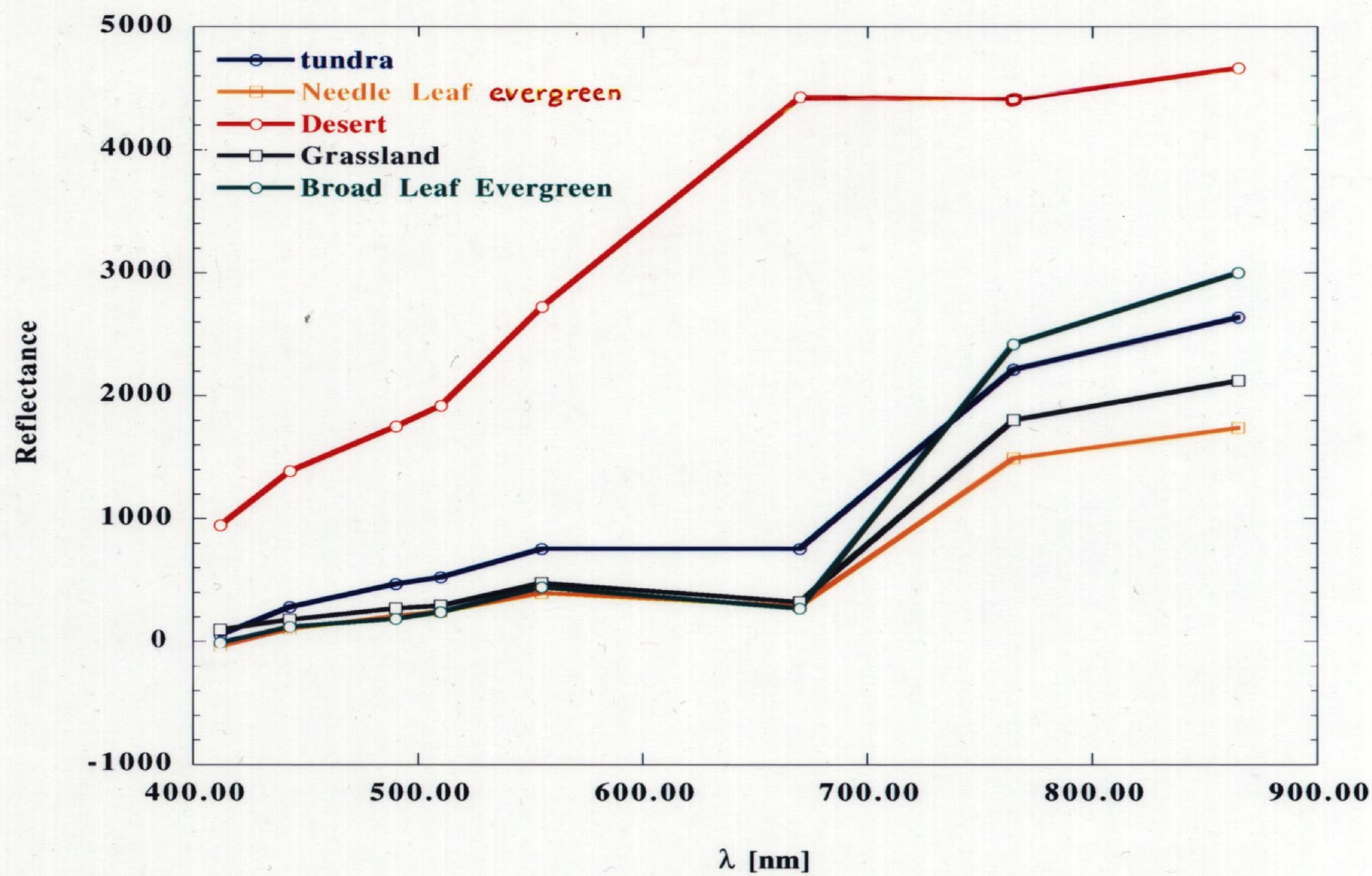
SeaWiFS 8-km 15-day Minimum Blue Composite

True Color Composite Image — Red: 0.670 μm; Green: 0.550 μm; Blue: 0.443 μm

September 16 – October 2, 1997

SeaWiFS Global Minimum-Blue Example

- Global Image
  - SeaWiFS data at 8 km resolution
  - 15-day minimum-blue global composite, 9/16–10/2, 1997
  - True color composite of SeaWiFS bands :
    - Red: 0.670 μm
    - Green: 0.550 μm
    - Blue: 0.443 μm
- Results
  - Land covers nicely separated—forests, semiarid regions, deserts, snow and ice
  - Lots of ocean color detail
  - 15 days, 8-km still leaves significant areas of cloud cover



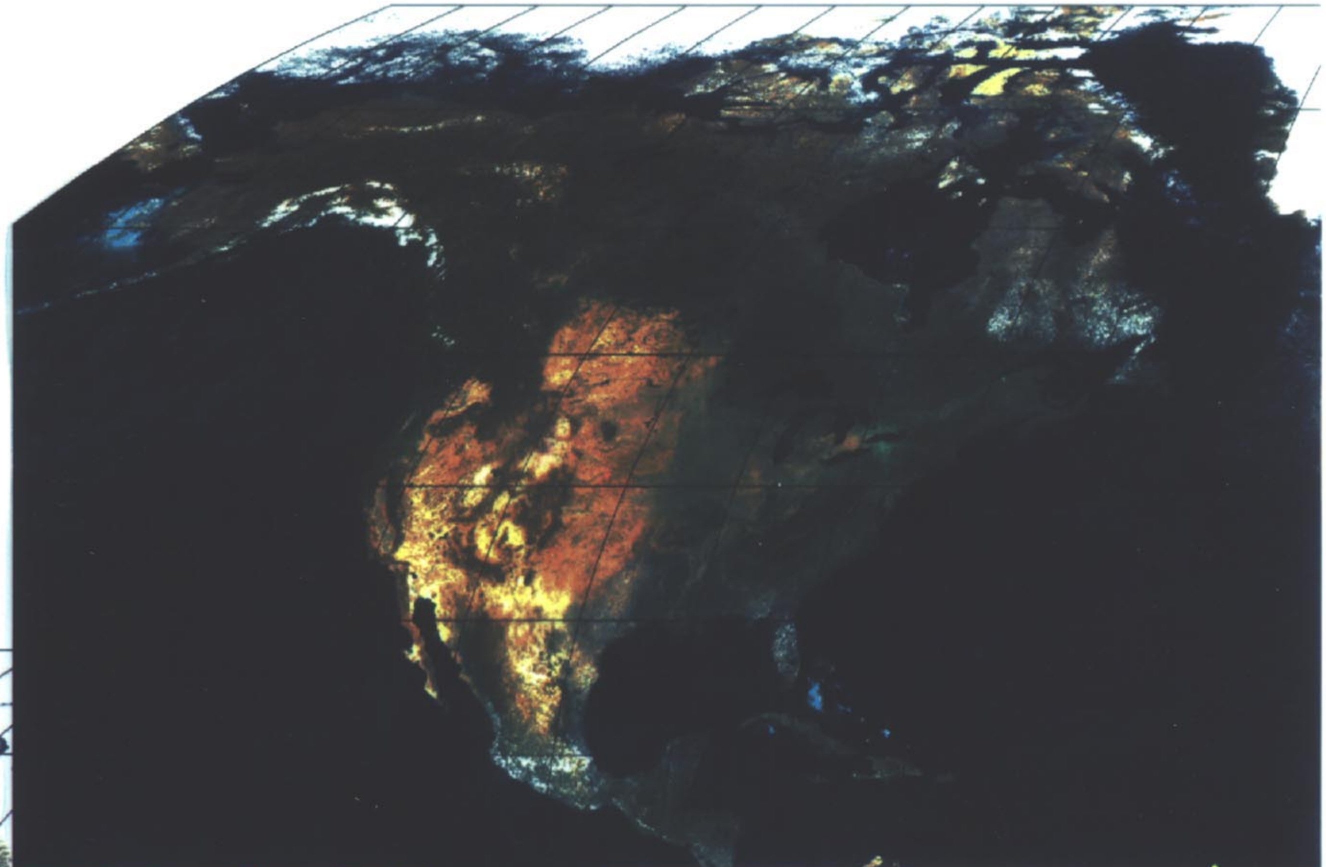
tundra
Needle Leaf evergreen
Desert
Grassland
Broad Leaf Evergreen
Reflectance
5000
4000
3000
2000
1000
0
-1000
400.00
500.00
600.00
700.00
800.00
900.00
λ [nm]

Spectral Plots of Composite Data

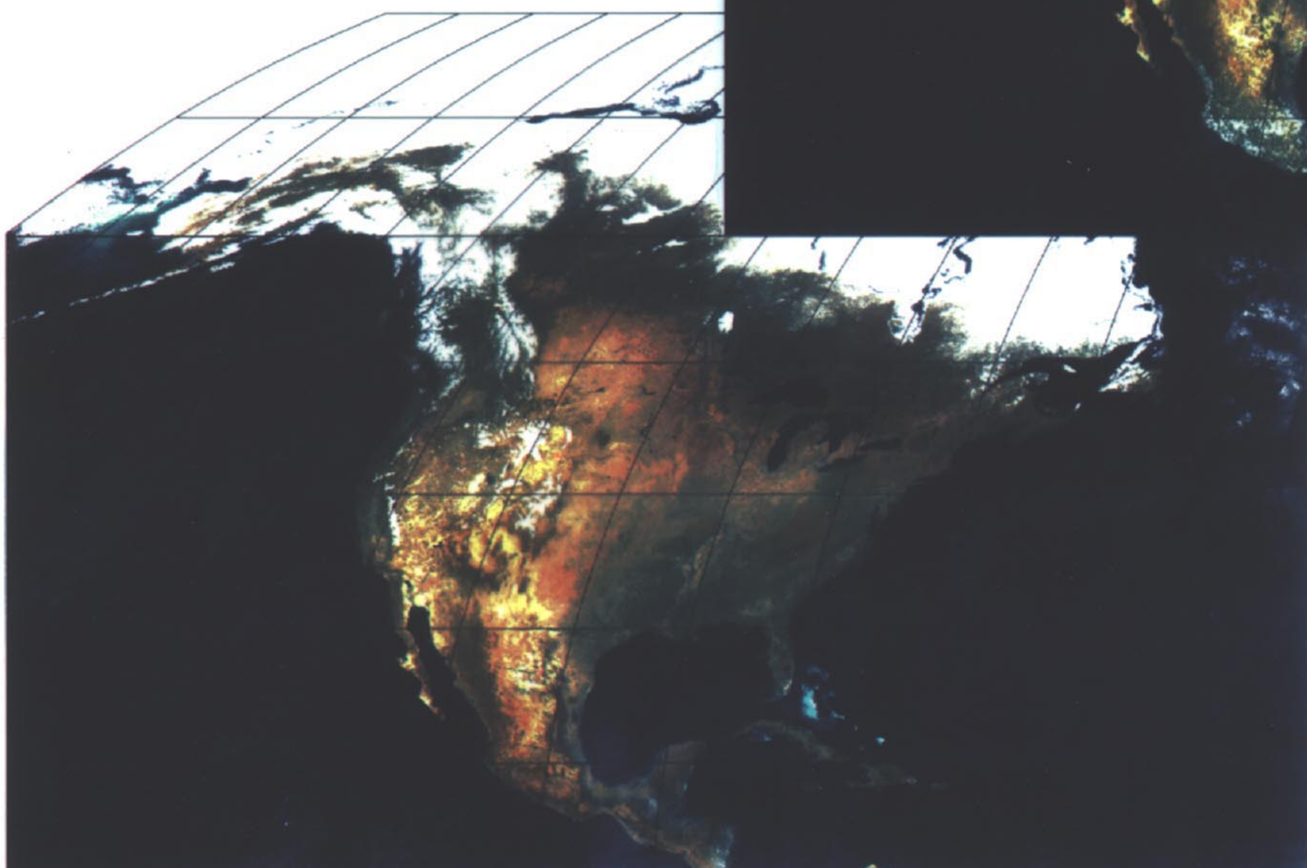
- Spectral Plots
  - Broadleaf forest, 9/98
  - Tundra, 6/98
  - Desert, 9/98
  - Grassland, 6/98
- Results
  - Cover types well differentiated in 8 SeaWiFS bands
  - Provides confidence in minimum-blue composited data

Seasonal Variation in SeaWiFS Composites

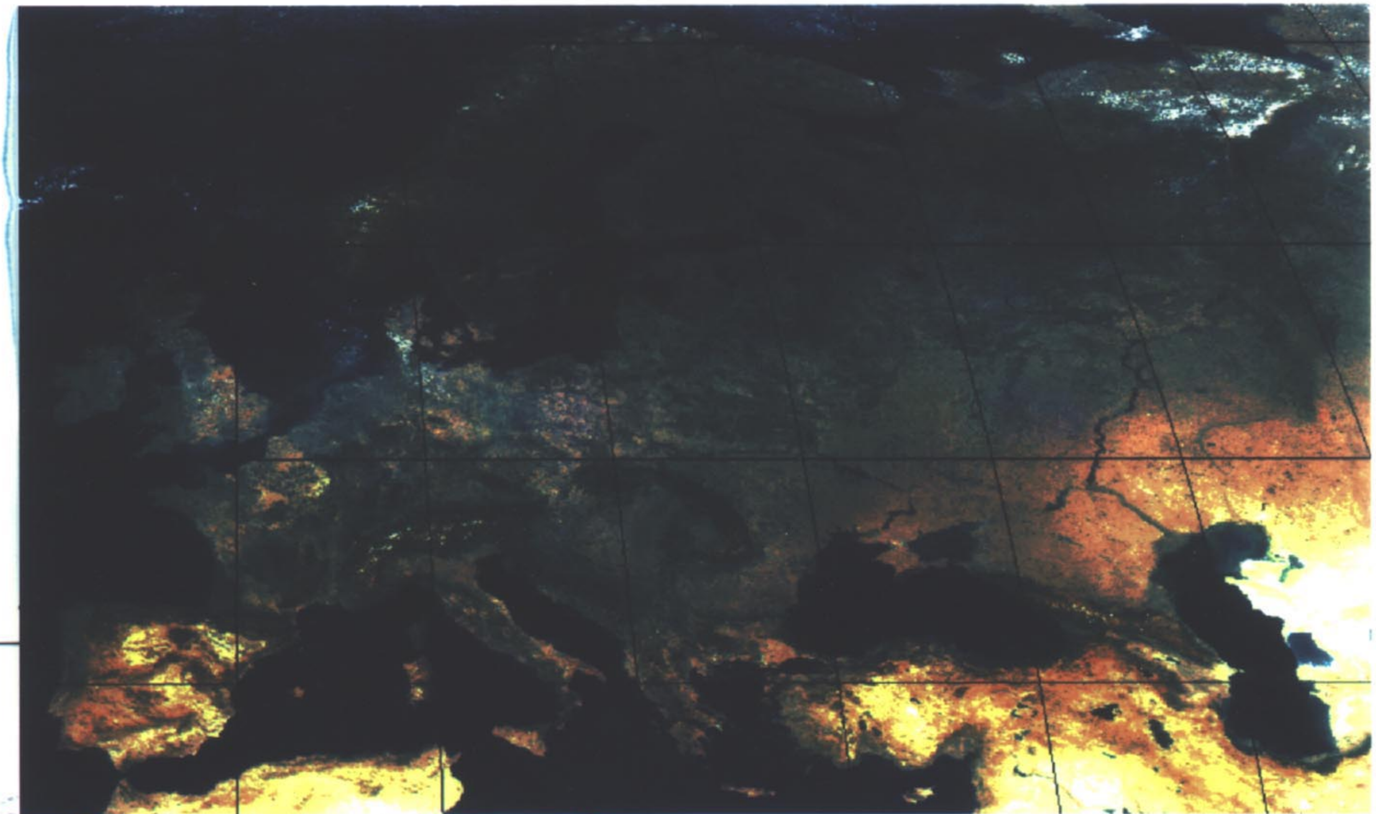
- Image Comparisons
  - North America
    - April vs. September
  - Northern Europe
    - February vs. September
  - South America
    - April vs. September
  - Africa
    - April vs. September
  - Australia
    - February, April, June, September



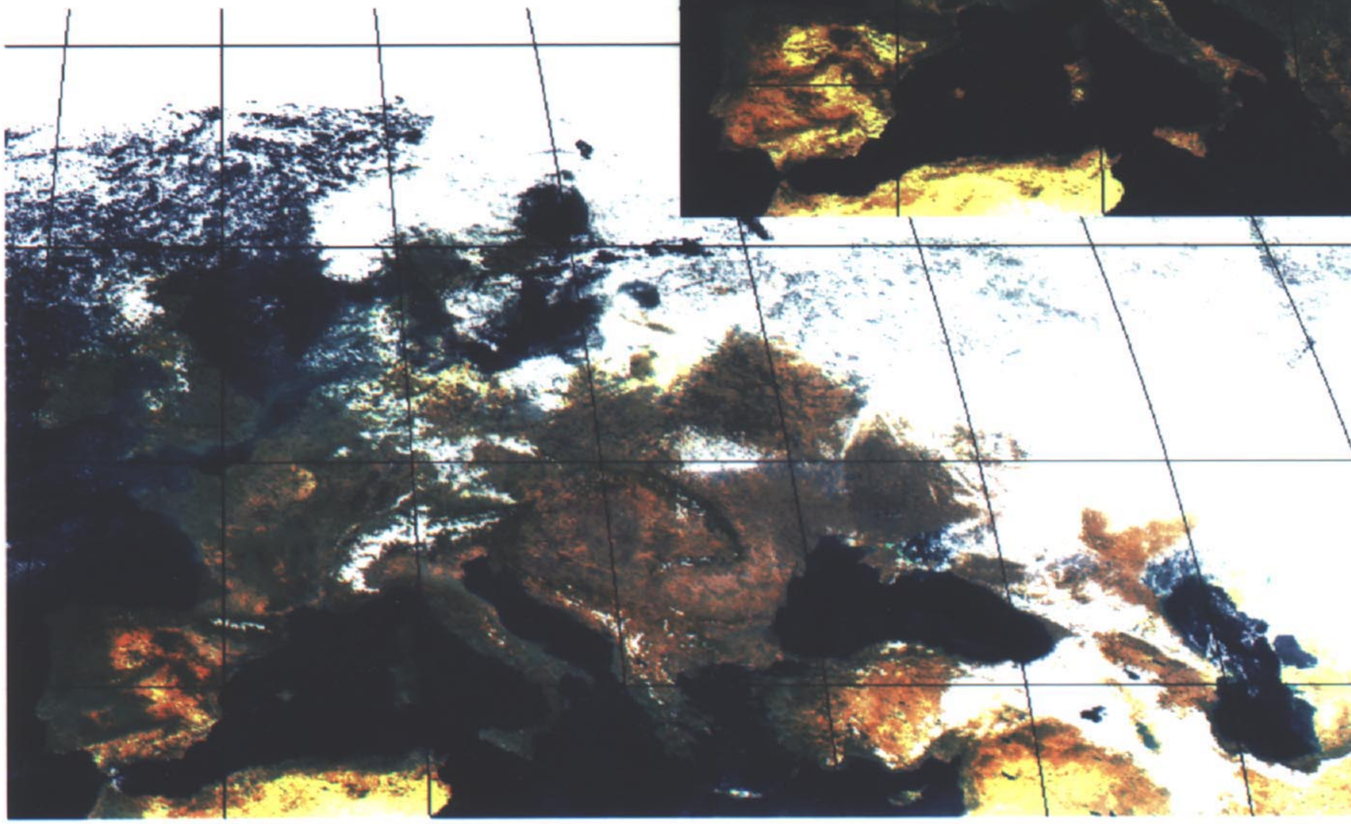
September 1998



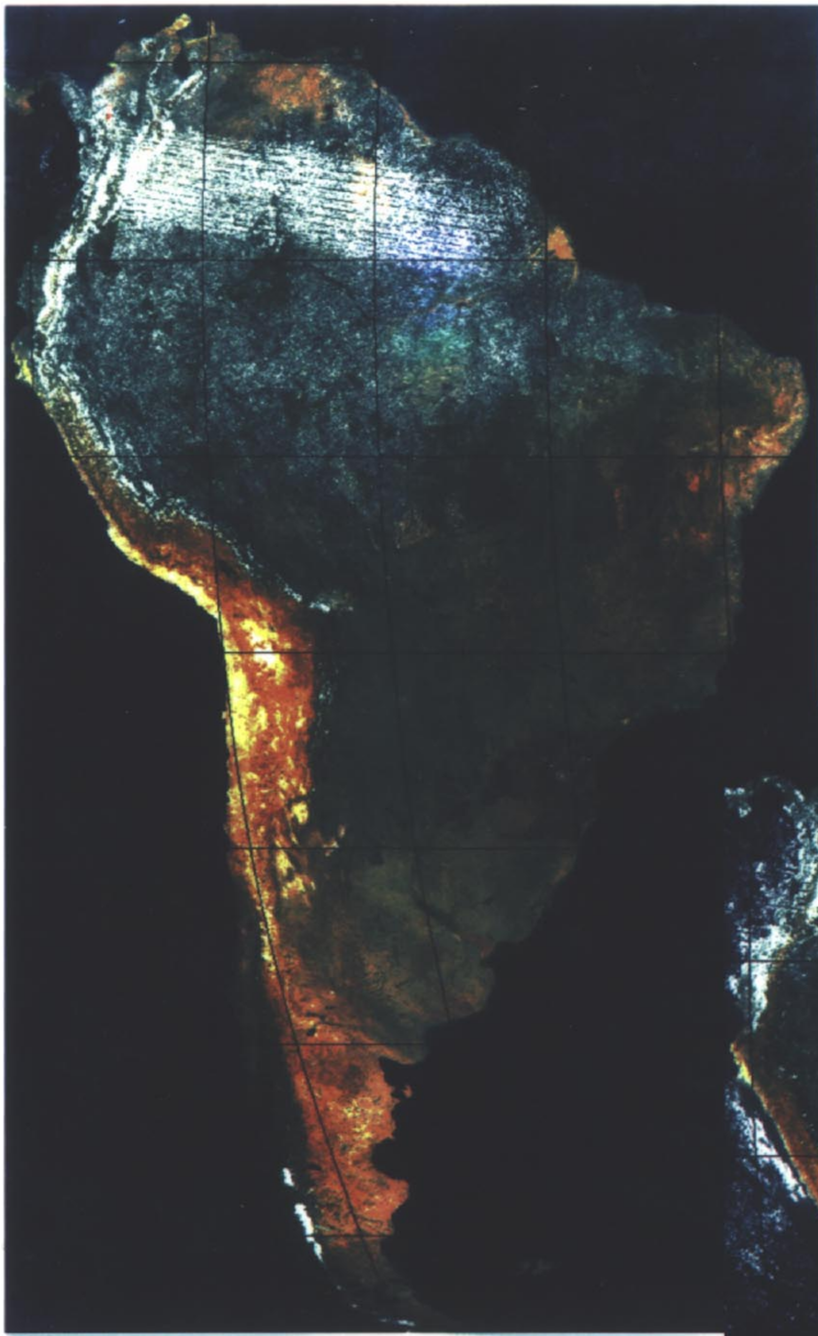
April 1998



September 1998

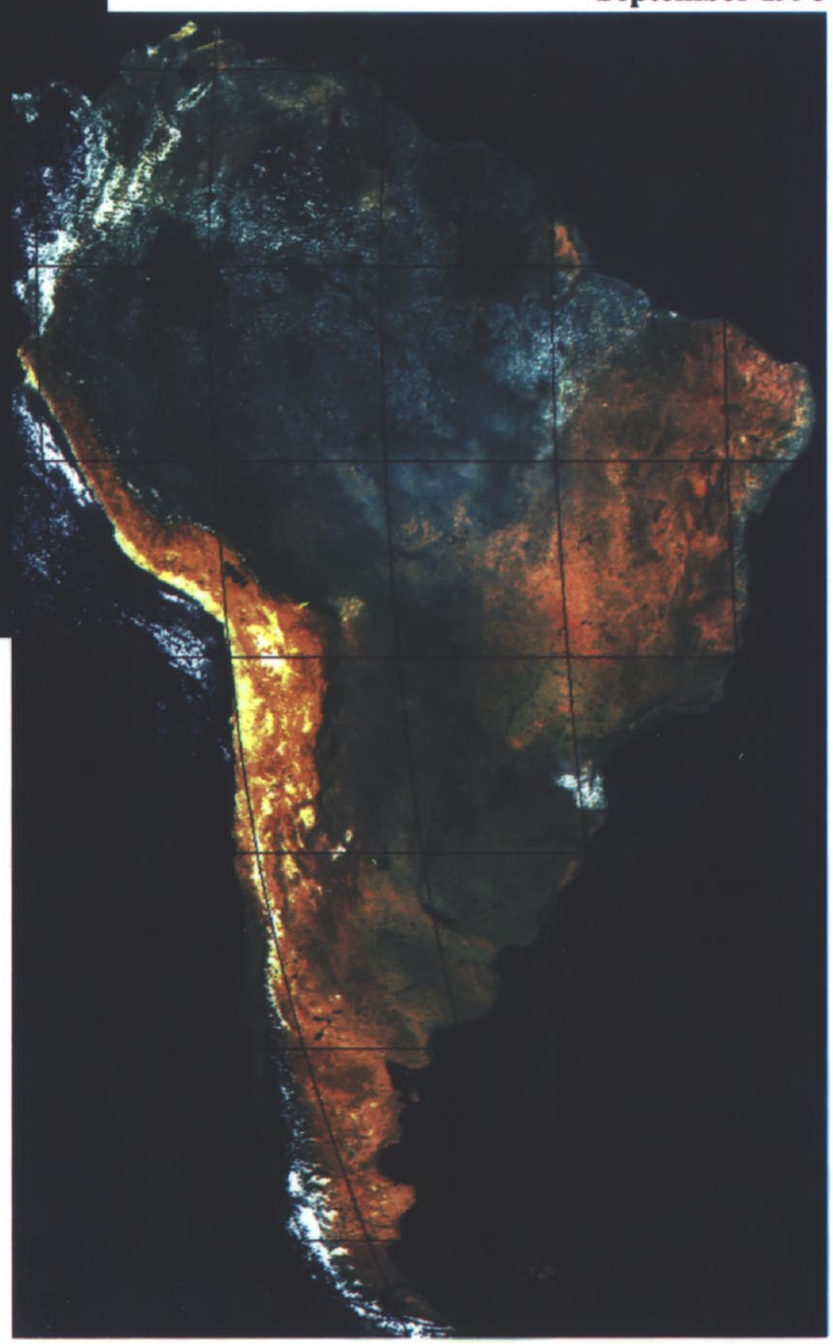


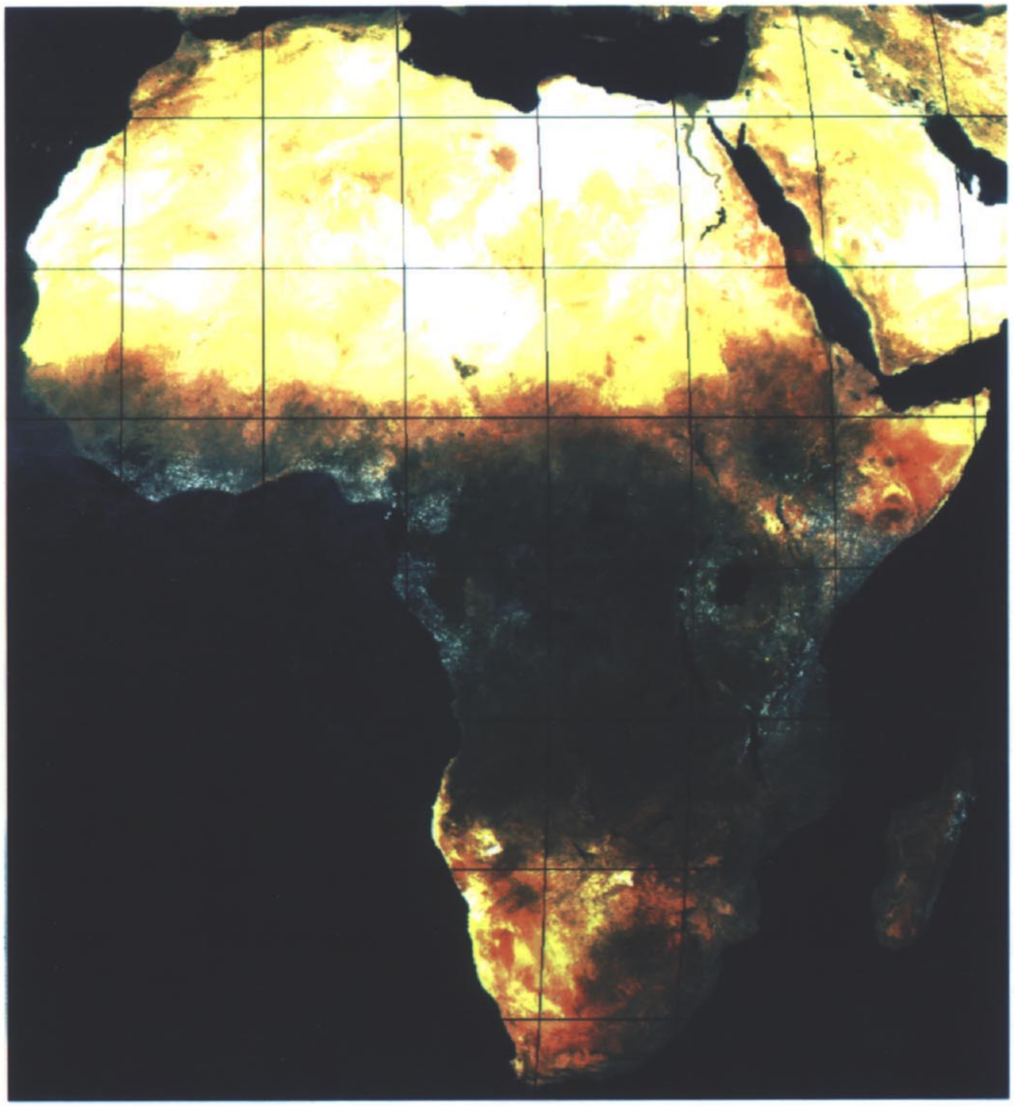
February 1998



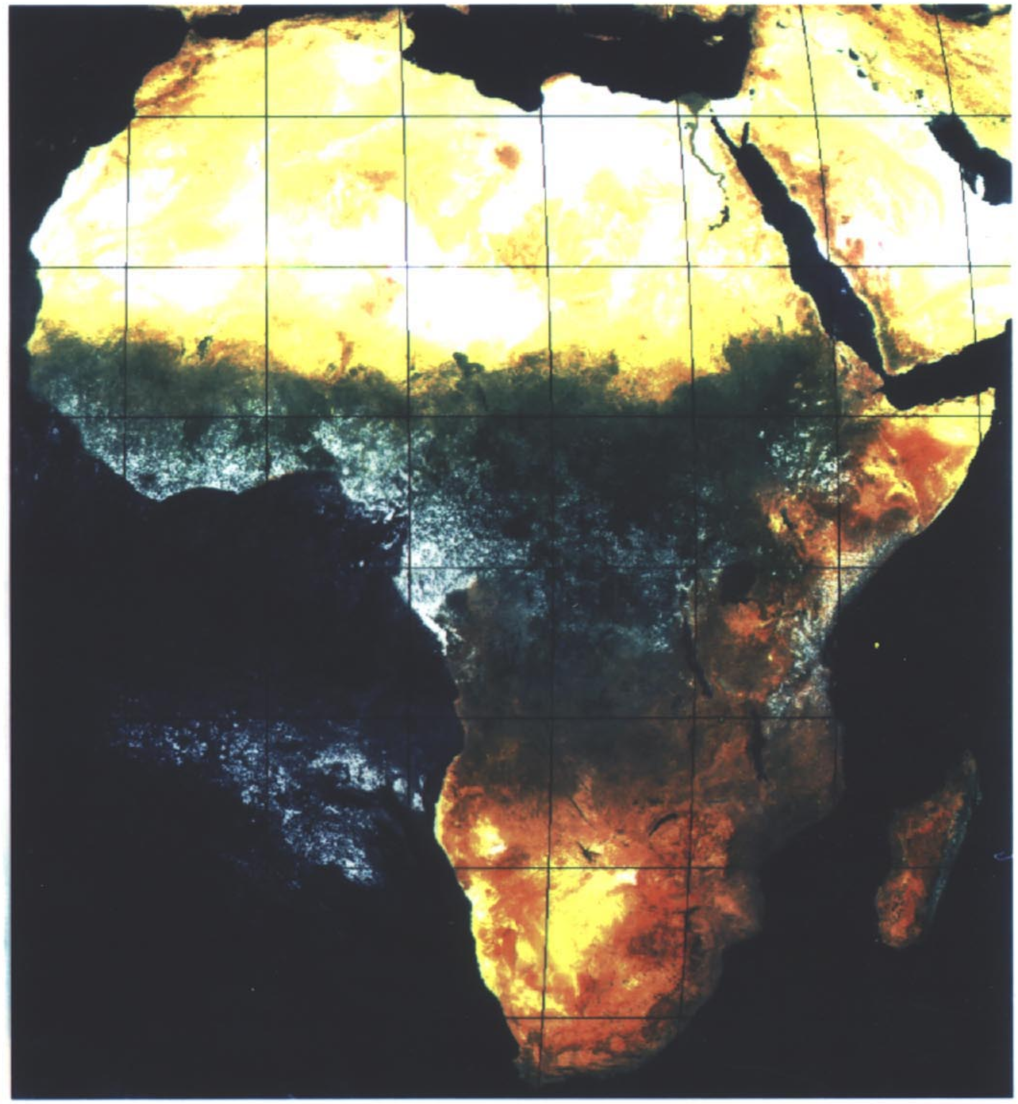
April 1998

September 1998





April 1998



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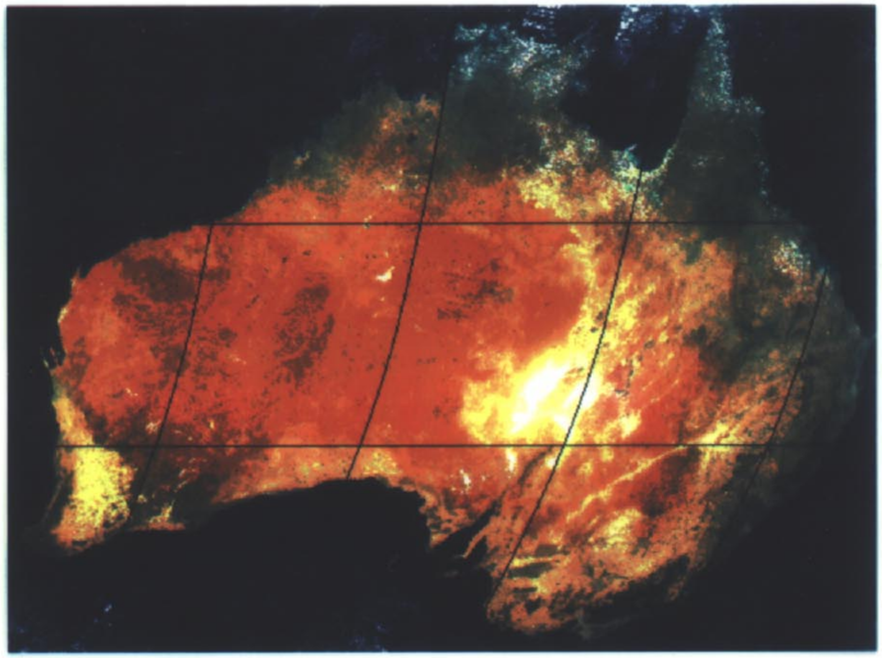
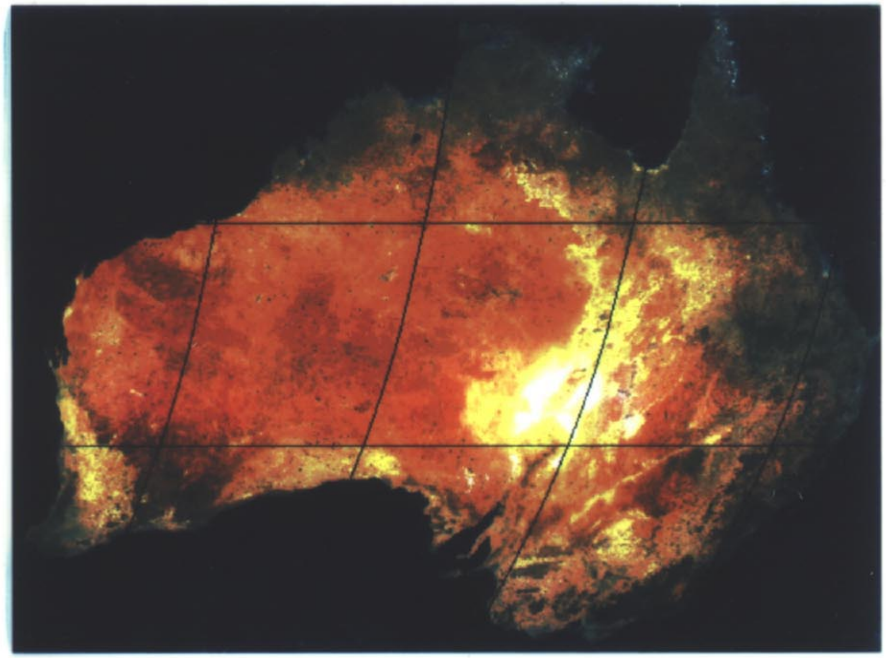
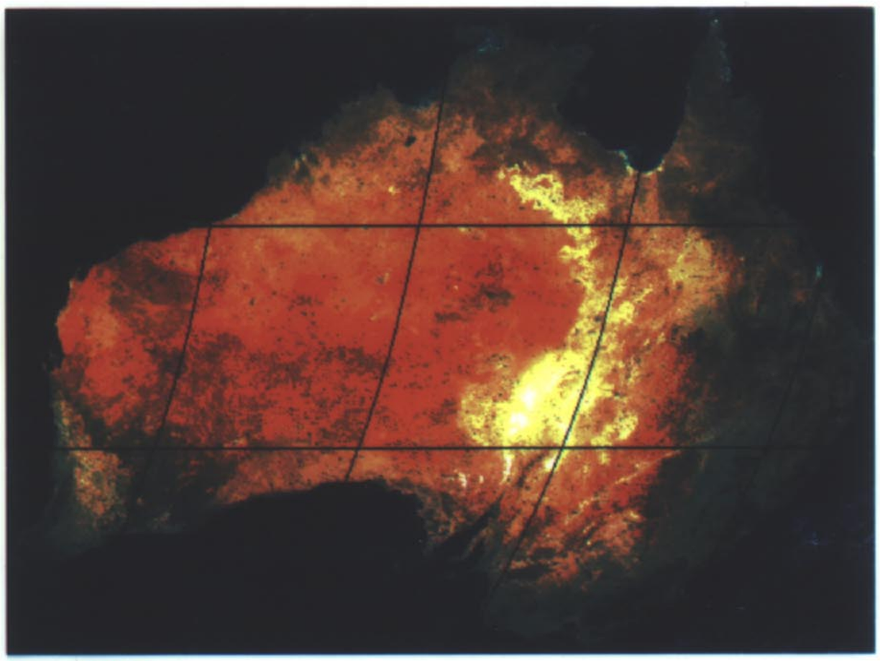


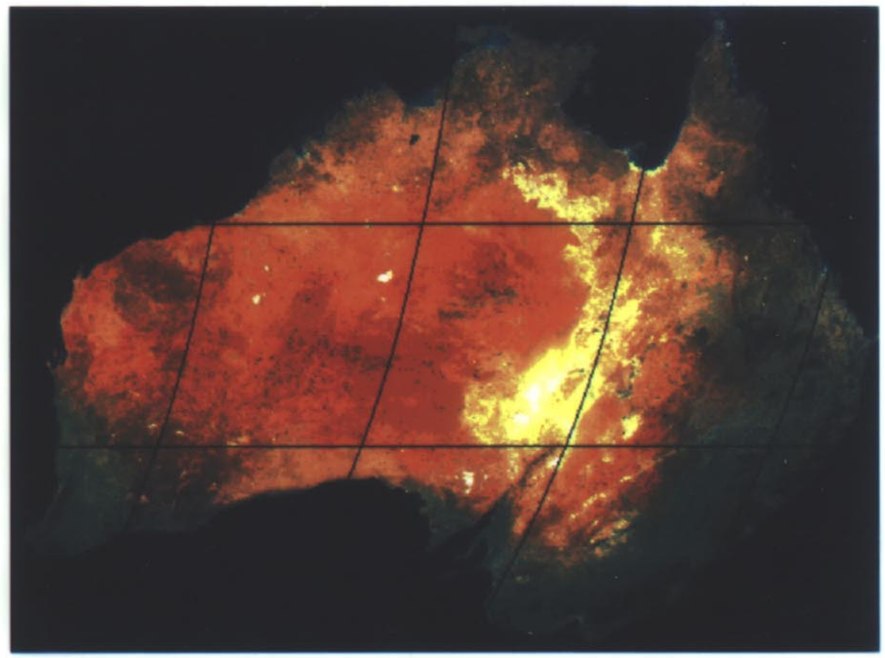
February 1998



April 1998



June 1998



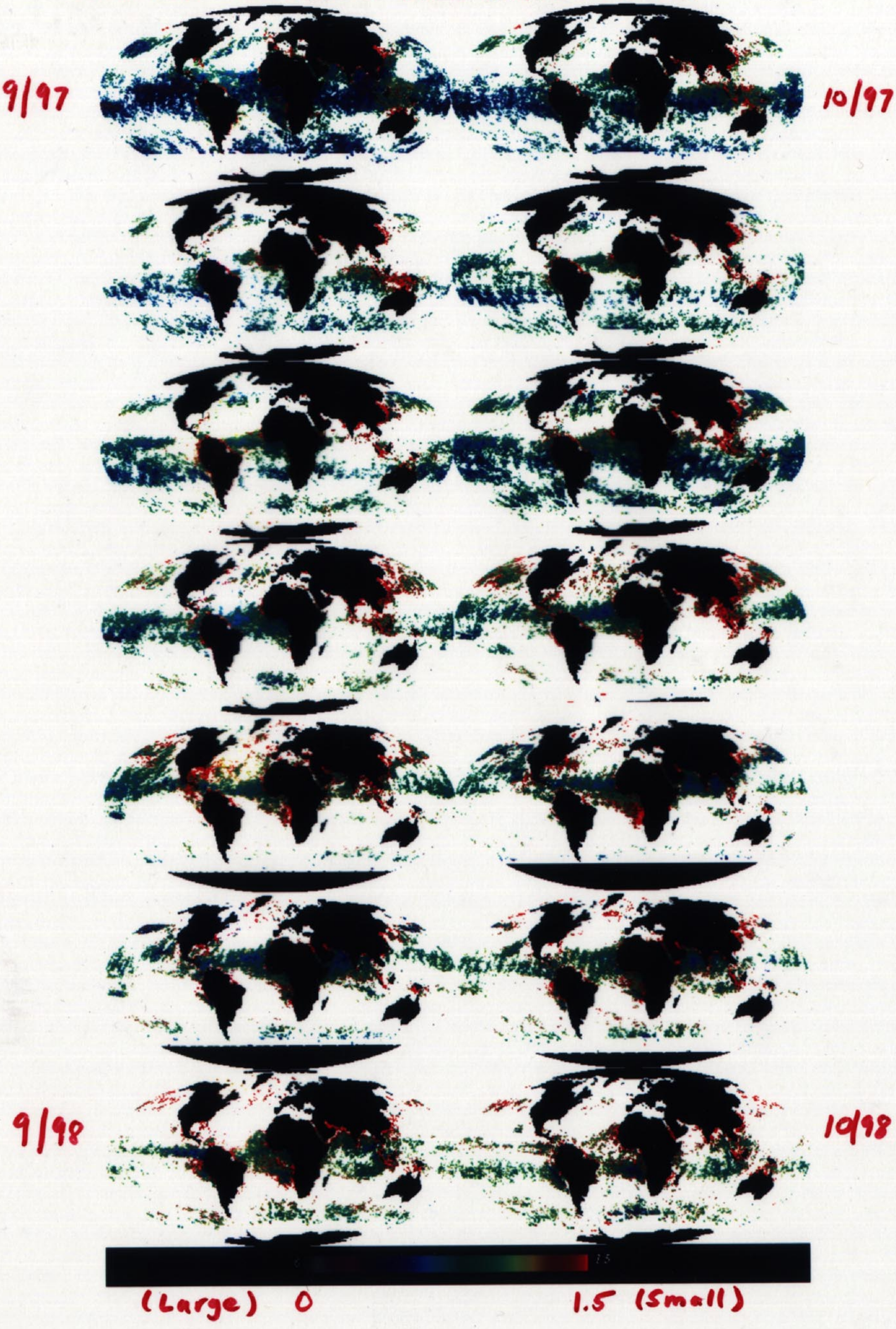
September 1998

Prototype Aerosol Retrievals

- Aerosol Optical Thickness over Oceans (Red Band)
  - Derived from minimum-blue monthly composite
  - 14 monthly images: September 97–October 98
  - Features:
    - September–October 97: Smoke from fires in equatorial band
    - Seasonal variation in optical thickness tracks seasons
- Aerosol Size Parameter
  - ln (radiance@670 / radiance@865)
  - 14 monthly images: September 97–October 98
  - Features:
    - Smoke aerosols generally larger (blue colors)
    - Saharan dust larger (blues) than kalahari dust (red)

SeaWiFS Aerosol Optical Thickness (Red Band)

SeaWiFS AEROSOL SIZE PARAMETER



Bidirectional Reflectance/Albedo (MOD43)

- Objective:
  – Quantify angular variation in reflectance of land surface covers and estimate albedo for energy balance and climatic studies
- Features:
  – Utilizes seven land bands of MODIS data as gridded in a 16-day period
  – Adds MISR data in postlaunch
  – BRDF shape is fit to a semiempirical model derived from simplifications of physical models of surface scattering
  – BRDF is integrated to provide spectral albedo measures independent of atmospheric effects
  – Visible, infrared, and broadband albedos provided
  – Level 3, land bands only, 1-km grid, 16-day repeat

BRDF/Albedo Prototype Using AVHRR, GOES

- New England Dataset
  - New England region, September 1995
  - Imagery mapped to 1 x 1 km grid using orbital models, additional corrections, 400 x 402 grid, with residuals of 0.4 km
  - All data atmospherically corrected using MODTRAN, 6S, and aerosol profiles inferred from surface visibility observations
- AVHRR Data
  - NOAA–14 (afternoon orbit) HRPT data, received locally by USAF
  - Cloud-cleared using SERCAA algorithm
  - Radiometric calibration after Rao and Chen (1996)
- GOES–8 Imager Data
  - VIS channel (similar to AVHRR Red)
  - Radiometrically calibrated from GOES Team data
  - Cloud clearing using temporal differencing

New England BRDF/Albedo Prototype, Cont.

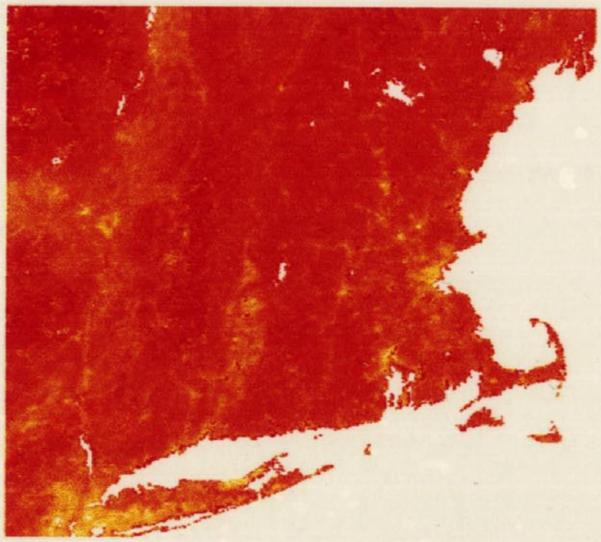
- Approach
  - BRDF / Albedo model fitted to all cloud-free observations
  - Directional-hemispherical albedo (black-sky albedo) mapped for for 0°, 45°, and 70° sun angles
  - Bihemispherical albedo (white-sky albedo) also mapped

BOSTON University

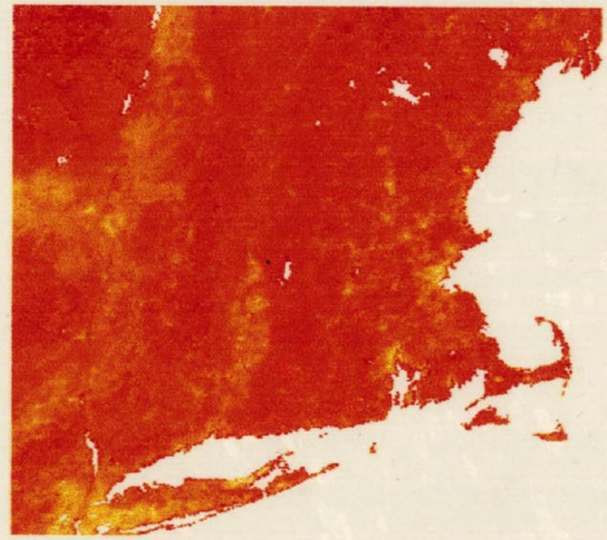
BRDF and Albedo from EOS–MODIS and MISR

AVHRR-GOES PROTOTYPE, RED BAND

Solar zenith angle–dependence of directional–hemispherical albedo

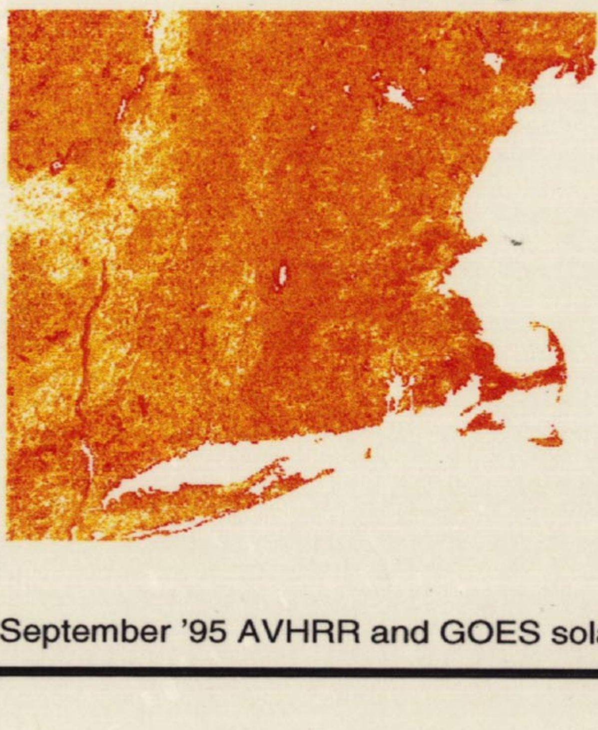


Solar zenith angle: 0 degrees

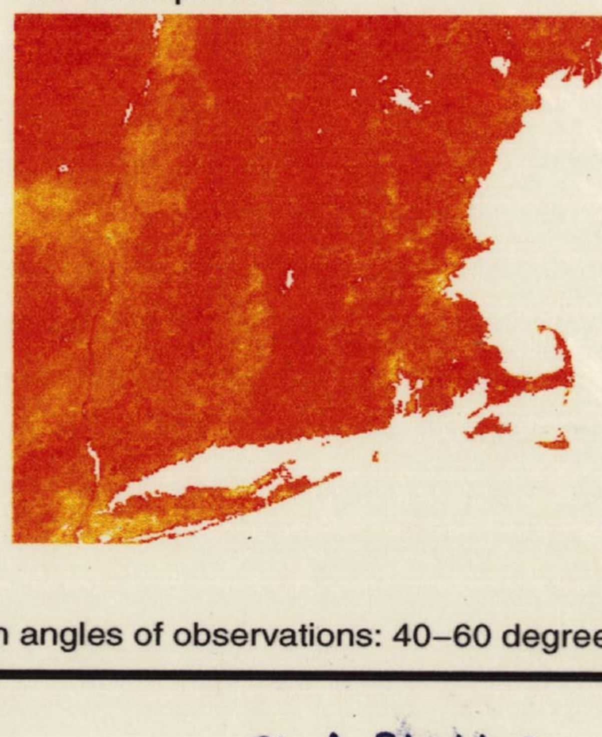


45 degrees

70 degrees



bihemispherical



September '95 AVHRR and GOES solar zenith angles of observations: 40–60 degrees

PI: A. Strahler

Global Broadband Albedo Database Prototype

- Objective
  - Provide a global, at-launch, broadband albedo database to initialize BRDF/Albedo algorithm
  - Merge field BRDF observations, land cover, and AVHRR data
- Approach
  - Define 25 land cover classes with contrasting BRDF shapes
    - Used Olsen classification labels from USGS 1-km database
    - Created summer and winter versions (*e.g.*, with and without background snow)
  - Fit Li-sparse/Ross-thin BRDF kernel model to 68 field BRDF datasets to provide BRDF shapes for these classes
  - Adjust magnitude of shape for each pixel using AVHRR observation from monthly NDVI composite, red and NIR bands
  - Apply narrow- to broadband conversion using a vegetation spectrum and typical downwelling spectral irradiance measurements

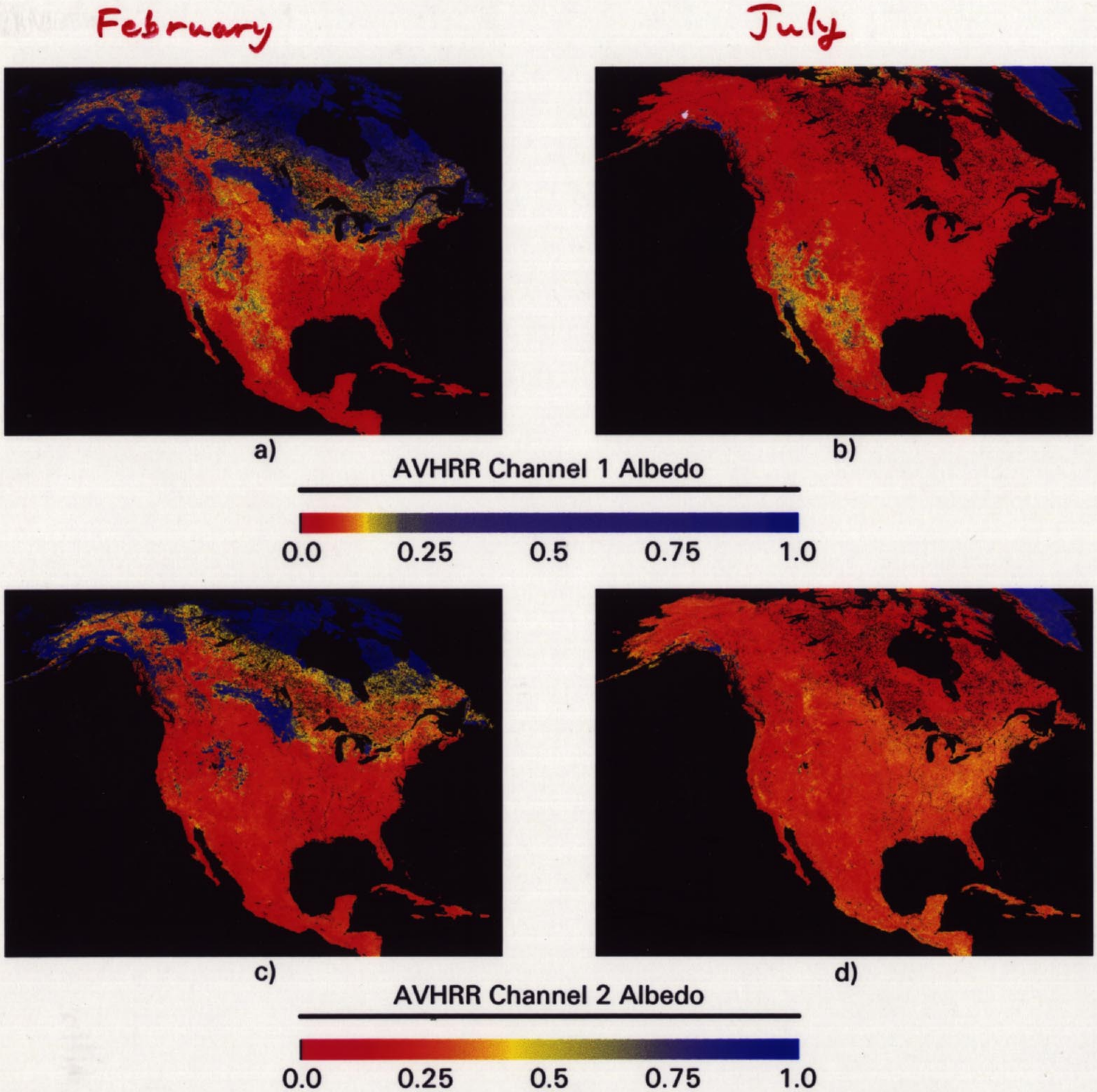


Figure 5: North American white sky albedos (a) AVHRR channel 1 winter spectral albedo. (b) Channel 1 summer spectral albedo. (c) Channel 2 winter spectral albedo. (d) Channel 2 summer spectral albedo.

North American Albedo Prototype

- Narrowband Red and NIR White-Sky (Angle-averaged) Albedo
  - February and July images for each band
  - Red band:
    - Strong winter-summer contrast due to snow
    - Barren areas in southwest increase in summer
  - NIR band:
    - Again, strong winter-summer contrast from snow
    - Higher albedos over croplands
- New England Broadband Black-Sky (Angle-dependent) Albedo
  - Comparison of SZA=0° with SZA=80° shows well-known increase of albedo with increase in SZA
  - New York area insets show that albedo of a landscape of random protrusions (Manhattan and Bronx) remains constant, following theory of Roujean

Solar
Zenith
Angle = 0°
(Overhead)

Solar
Zenith
Angle = 80°
(near
horizon)

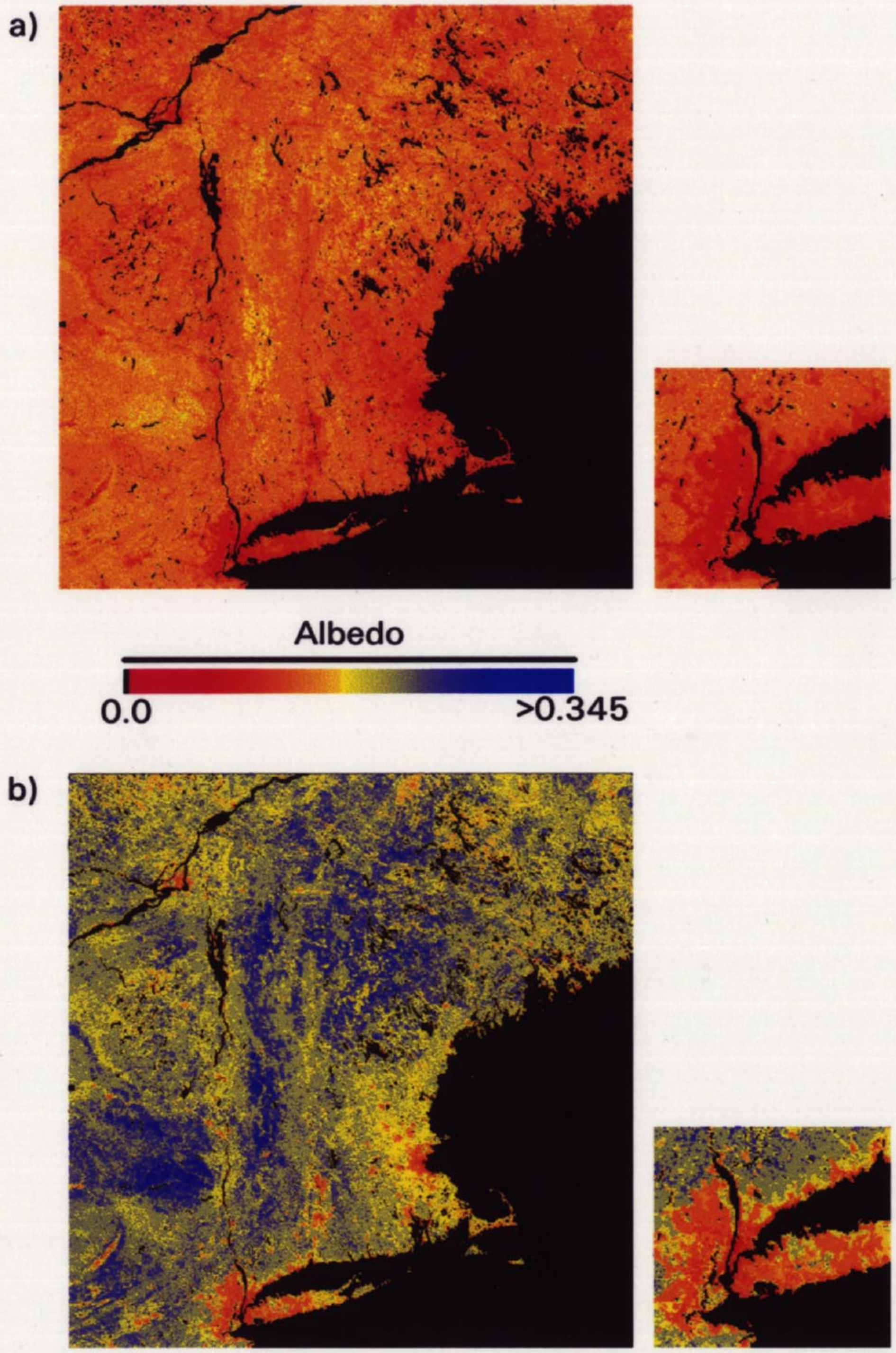
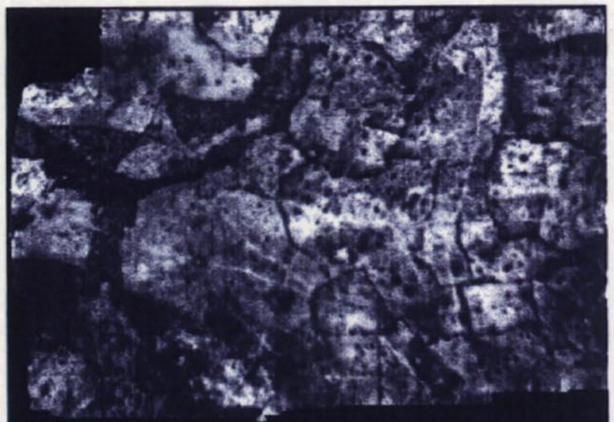


Figure 7: Summer full band black-sky albedo image. (a) Solar zenith 0°. (b) Solar zenith 80°.

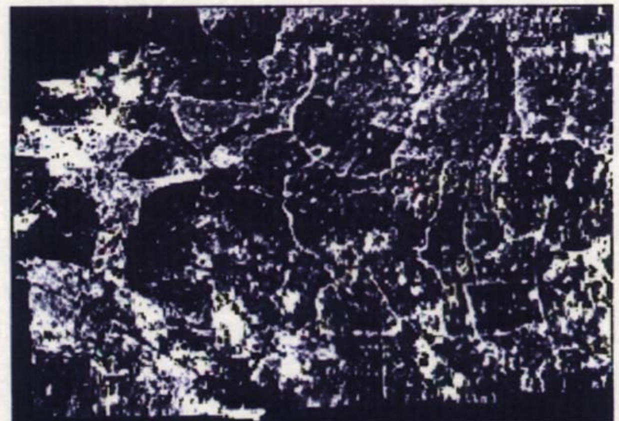
Structural Information in BRDF Shape

- Objective:
  - Examine values of kernel weights in Ross-Thick / Li-Sparse model for relationships with plant structure
- Approach
  - Use ASAS data for HAPEX-Sahel Niger site
  - Register multiangle images
  - Fit kernel models to all pixels in image
  - Map and photocomposite kernel values
- Result
  - Color composite easily identifies grasslands (yellow), millet agriculture (green), shrubs (red), and tigerbush (deep purple)

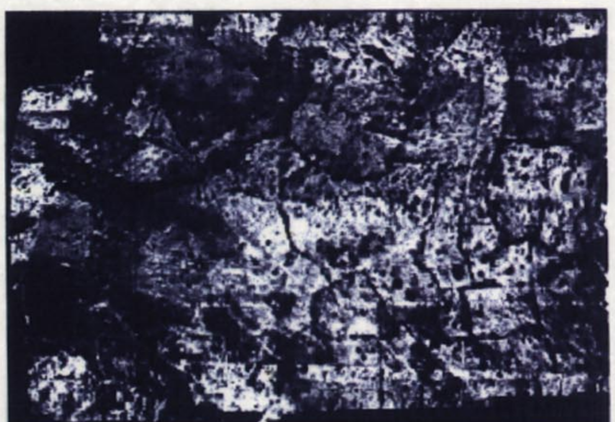
Results of BRDF Model Inversion



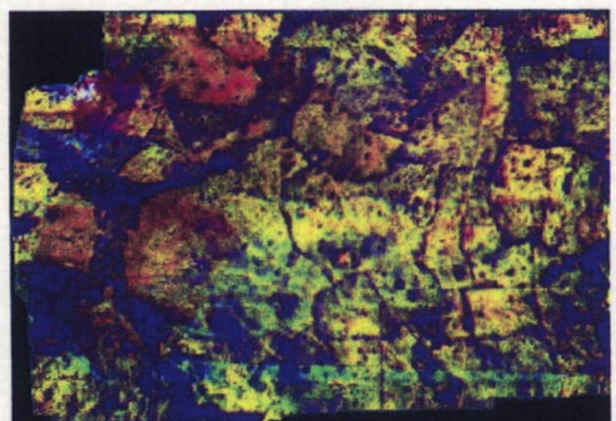
Isotropic Scattering



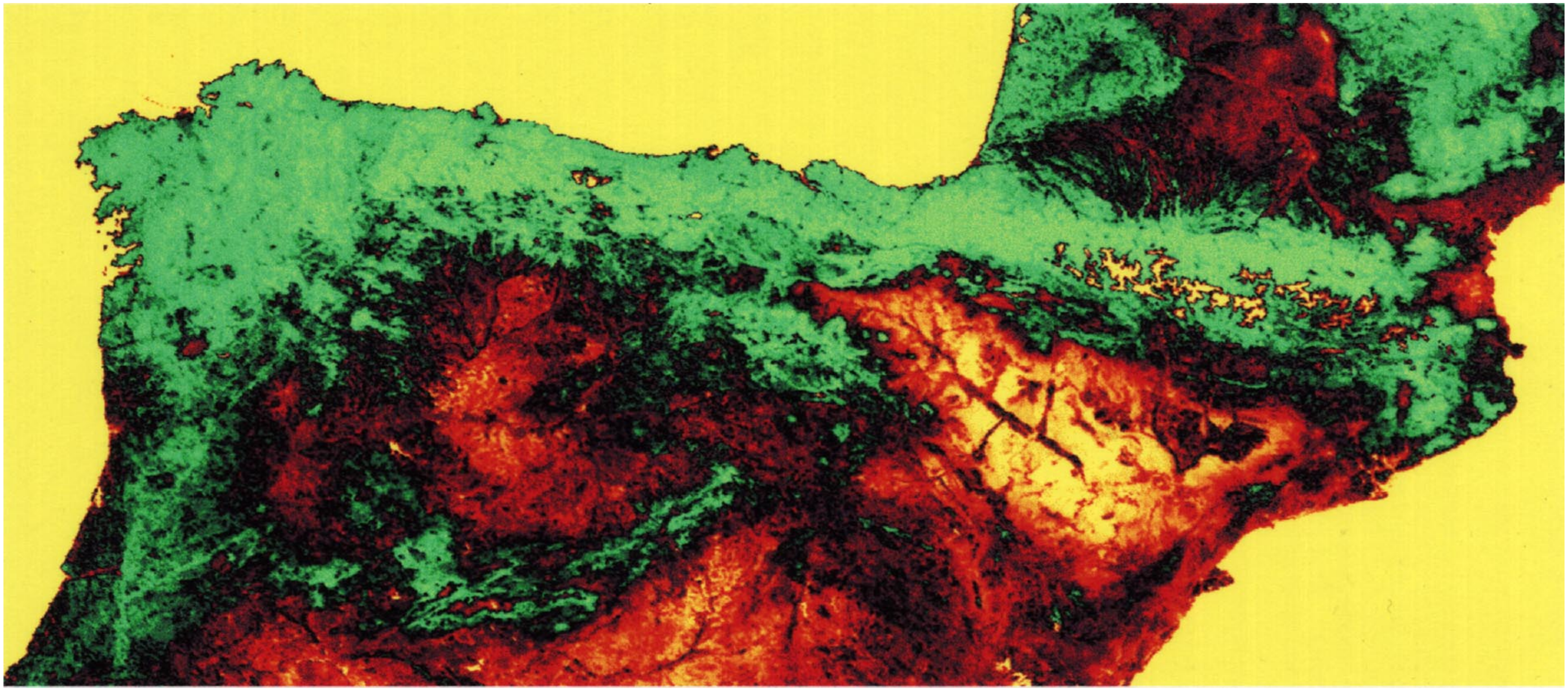
Geometrical-Optical Scattering

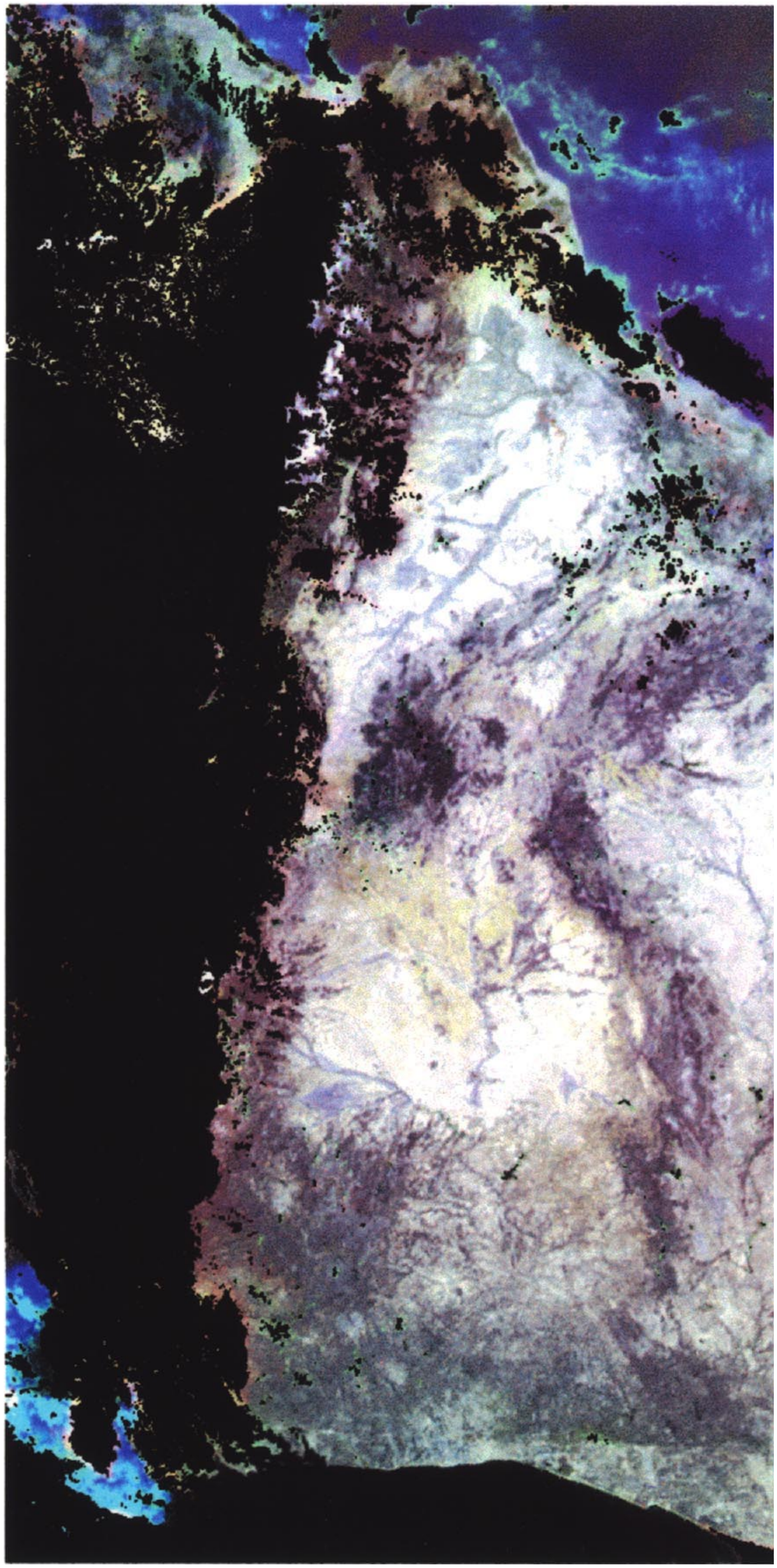


Volume Scattering



Iso (B), Geo (G), Vol (R)

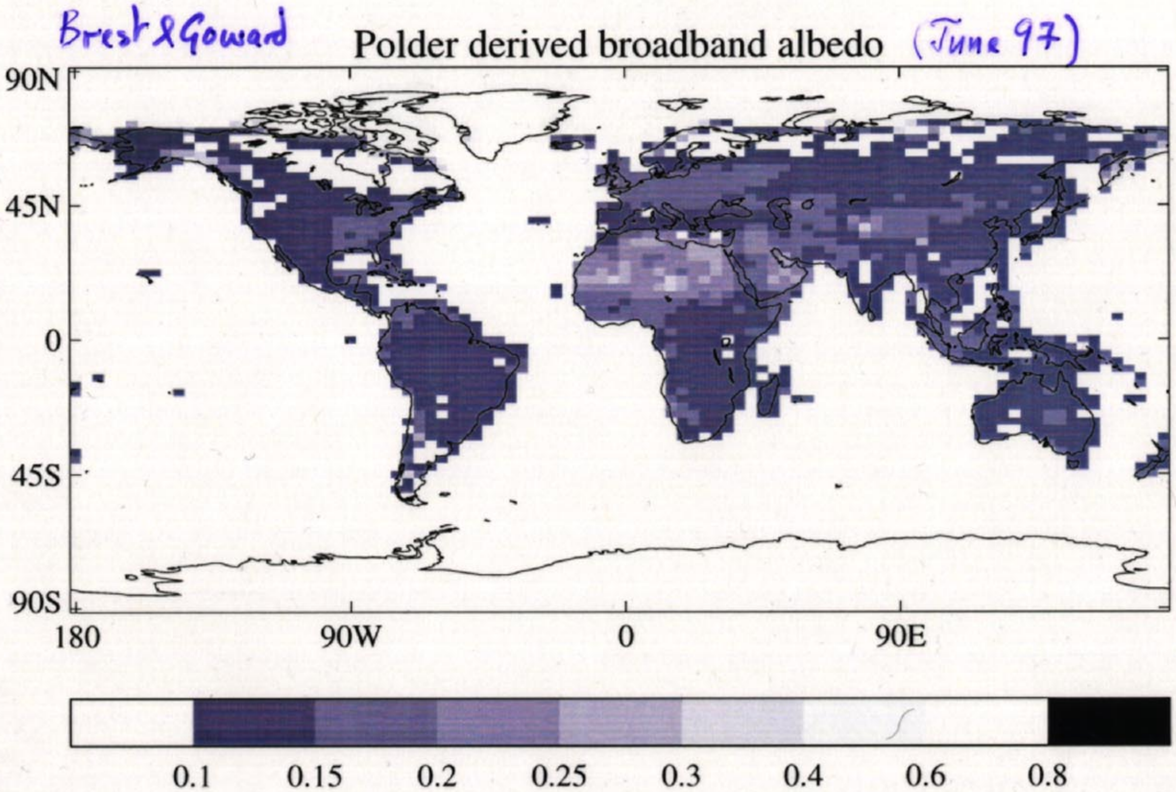


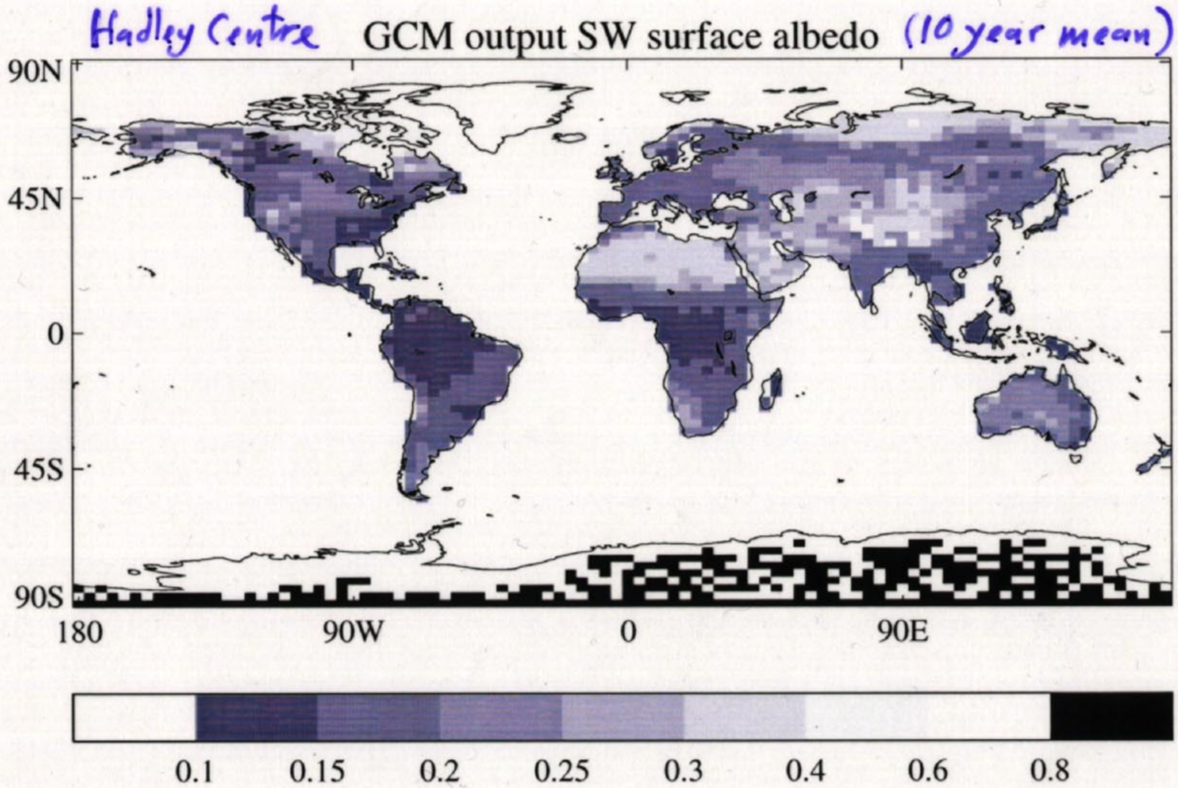


Prototyping with POLDER

- Northern Spain / Portugal Images
  - False color, NDVI show vegetation cover
  - Three-angle red image shows much more detail
- POLDER-Derived Broadband Albedo
  - Comparison of POLDER-derived albedos with GCM output from UK Hadley Center
  - Shows major differences, highlighting need for better surface albedo data in GCMs

Comparison of POLDER-derived and GCM output albedo





Land Surface Temperature (MOD11)

- Objective:
  - Provide surface temperature and emissivity information for input to surface energy balance and global climate models
- Features:
  - Multiband approach based on atmospheric molecular absorptions and radiative transfer simulations
  - Two alternative approaches:
    - Generalized split-window LST method: utilizes a knowledge base of regional and seasonal characteristics of land surfaces keyed to the MODIS Land Cover product
    - Day / night LST method: retrieves emissivities and temperature for land covers with variable emissivities—e.g., deserts, bare rock surfaces
  - Accommodates viewing angle and topographic (elevation) effects
  - Level 2, 1-km spatial resolution, clear skies only
  - Level 3 gridded product (1-km & 5-km) daily and on 8-day and monthly intervals provided

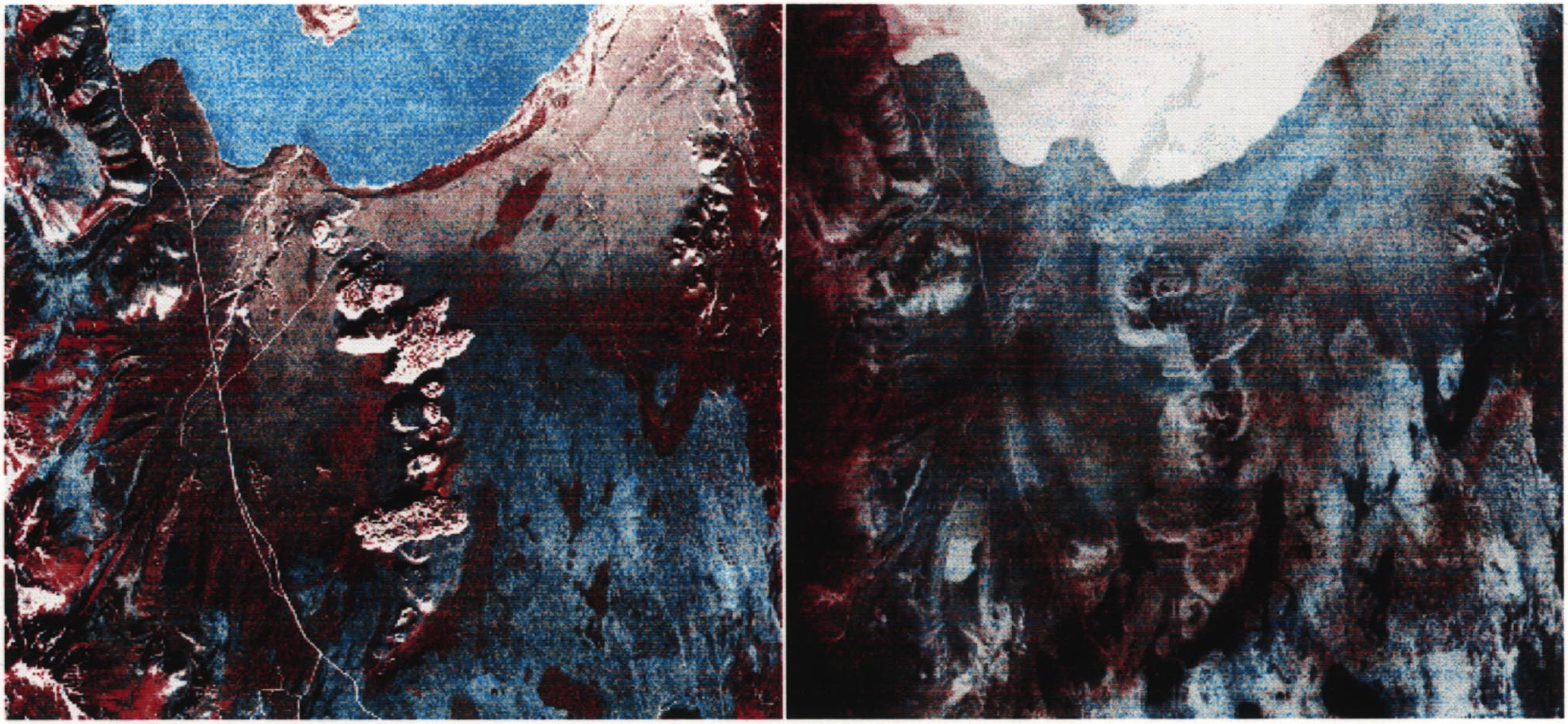
Prototyping Surface Temperature Retrieval with MAS—Snow Campaign

- Field Campaign near Mono Lake, CA, March, 1997
  - MAS day and night overflights
  - Field measurements using
    - 1 TIR spectrometer (3.5–14.0 μm, 25-cm FOV)
    - 6 broadband radiometers (10–13 μm, 1-m FOV)
    - 6 themisters a few mm below snow surface
    - radiosonde balloons launched during day and night flights
  - Four targets: Mono Lake water; thin ice on Grant Lake; snow-covered ice on Grant Lake; snow field
- Objectives
  - Acquire day-night MAS imagery for snow, ice, and cold water targets
  - Retrieve surface temperature / emissivity under thin cloud (cirrus) conditions
  - Test scaling of temperature retrievals from 100 m to 3.2 km pixels

Prototyping Surface Temperature Retrieval with MAS—Snow Campaign, Cont.

- Approach
  - Use field measurements and radiosondes to calibrate MAS channels
  - Add thin cirrus correction to MODIS LST algorithm
  - Retrieve for each pixel from day-night imagery
    - 7 emissivities in MAS spectral bands
    - Surface temperature
    - Air temperature
    - Water vapor depth
    - Cirrus optical thickness
  - Average pixels to collapse resolution, repeat retrievals for
    - 100, 200, 400, 800, 1600, 3200 m
  - Examine scaling means and variances

Fig. 1, Color composites of MAS images in bands 30, 42 and 45 enhanced with histogram equalization from field campaign in Mono Lake, CA, March 10, 1998.

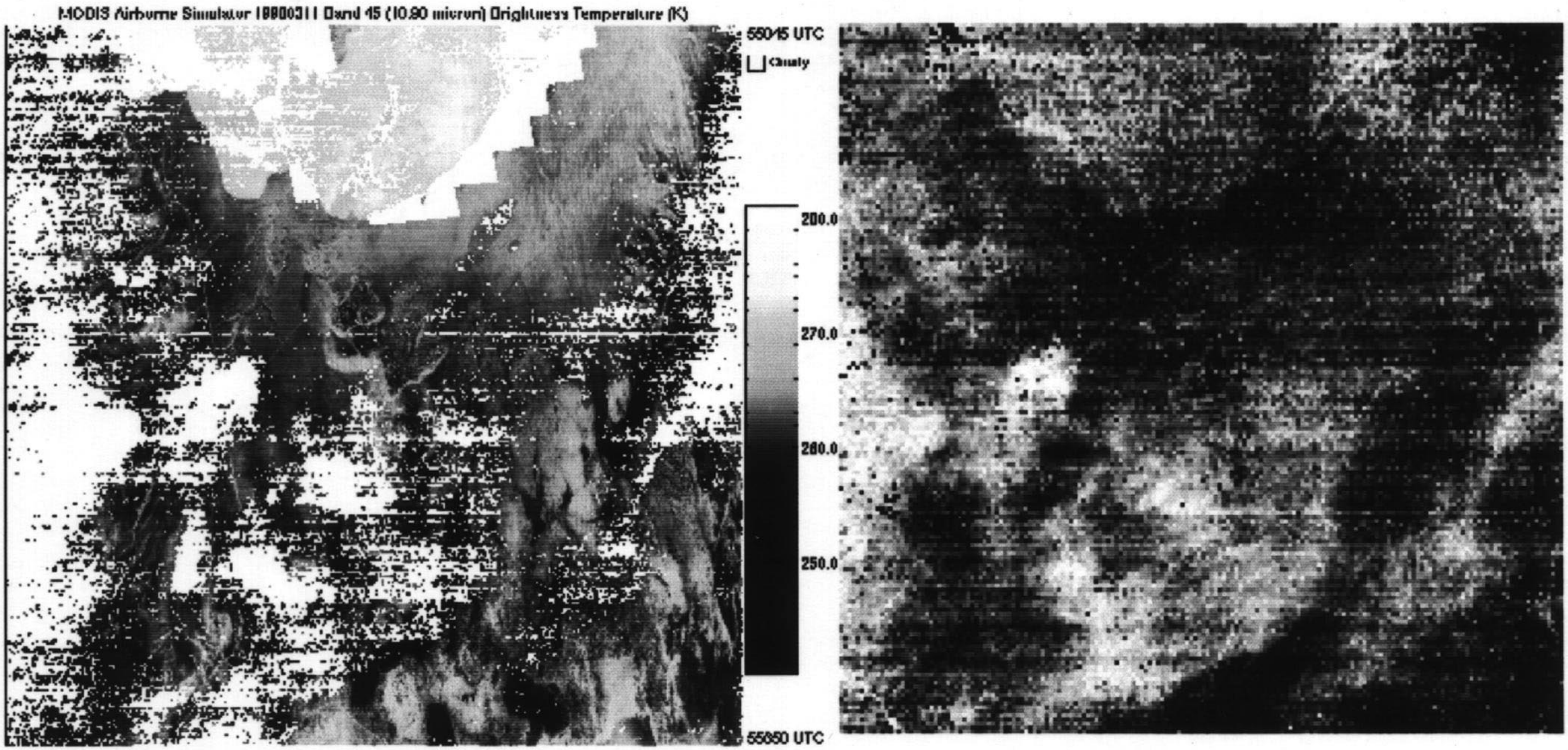


(a) around 11:30 PST **(b) around 22:00 PST**

Day and Night MAS Images

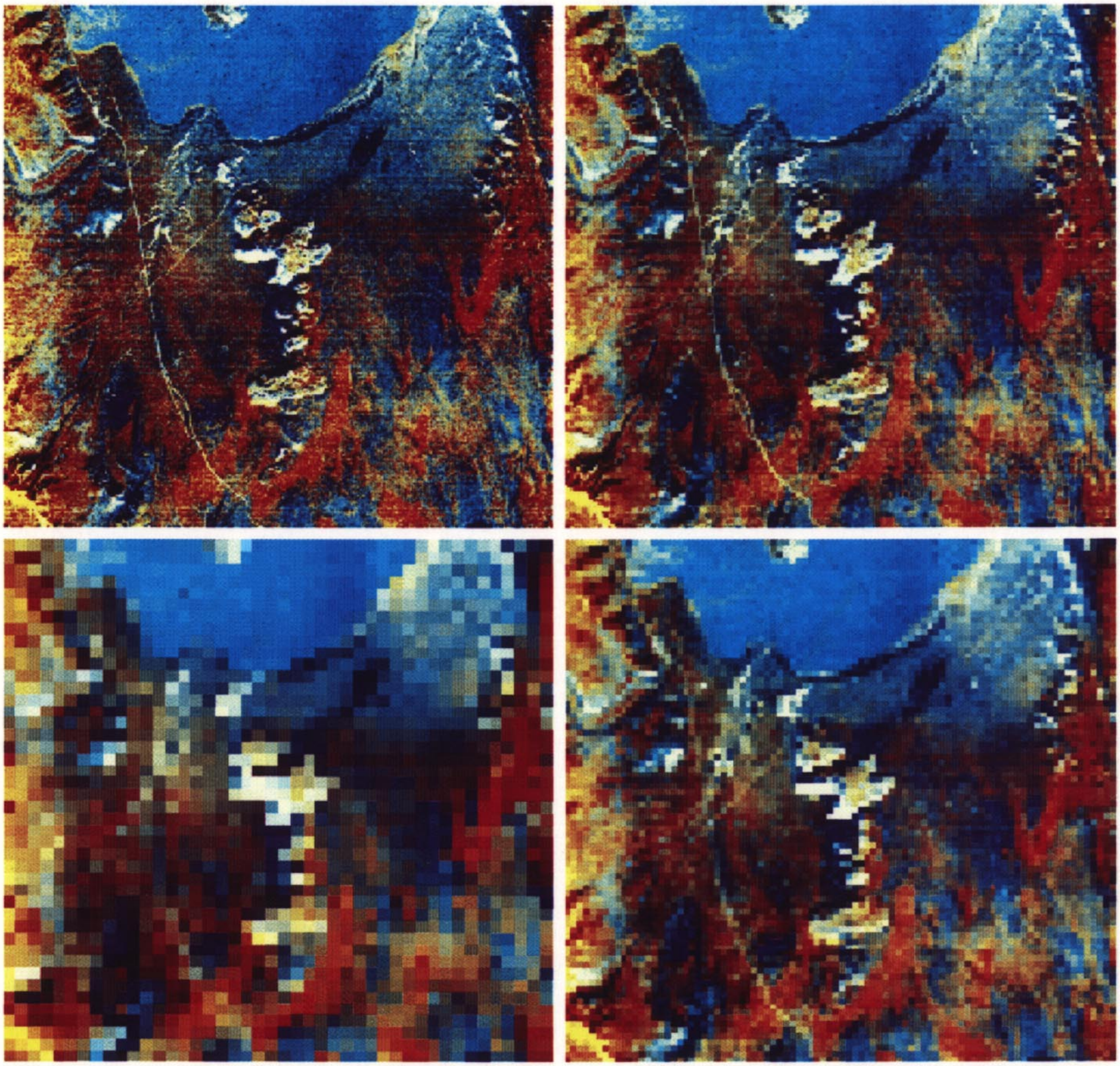
- MAS Images
  - Color composites of MAS Bands 30 (3.745 μm), 42 (8.467 μm), and 45 (10.975 μm)
  - Mono Lake; Mono Craters; snow field at 395 and Tioga Pass Road; Grant Lake
  - Day: 11:30 AM PST; Night: 10:00 PM PST
  - Low contrast in night imagery denotes high cirrus
- Cirrus Retrieval Images
  - Left: Mask of pixels detected by U. Wisconsin cloud-mask code
  - Right: Cirrus optical depth retrieved by enhanced LST algorithm
- Scaling Images
  - Color composite of retrieved day-night temperature difference, day temperature, night temperature

Fig. 2, Clouds detected by the UW cloud-mask code (a), and cirrus optical depth retrieved from MAS data by the enhanced day/night LST algorithm (b).



(a) (b)

Fig. 3, Color composites of day-night difference, day and night temperatures retrieved from MAS data at resolutions 100m, 200m, 400m, and 800m.



Retrieval Results

- Retrieval Table
  - Average temperatures, water vapor depths, and cirrus optical depths are nearly constant with resolution scaling
- Emissivity Table
  - Average emissivities also vary little with scaling
- Conclusions
  - Enhanced LST algorithm can retrieve and remove thin cirrus successfully, even over cold targets
  - Scaling up to GCM grid resolutions should not pose a problem for the LST algorithm

TABLE 4. Regional averages of land-surface temperature (T_s), air-surface temperature (T_a), column water vapor (wv), and night cirrus optical depth (a_{cir}) retrieved from day/night MAS data at different resolutions.

resolution (m)	T_s (°C) day	T_s (°C) night	T_a (°C) day	T_a (°C) night	wv (cm) day	wv (cm) night	a_{cir} night
100	2.932	-8.322	2.554	-1.292	0.314	0.282	0.057
200	2.910	-8.308	2.597	-1.193	0.316	0.281	0.060
400	2.896	-8.323	2.582	-1.183	0.316	0.281	0.062
800	2.896	-8.336	2.483	-1.252	0.315	0.281	0.063
1600	2.855	-8.363	2.473	-1.267	0.314	0.281	0.064
3200	2.962	-8.280	2.442	-1.298	0.314	0.282	0.065
maximum differences at all resolutions							
	0.10	0.08	0.16	0.12	0.002	0.001	0.008

Note: The differences are caused by the LST algorithm's error, instrument noise at higher resolutions, and spatial variations in thin clouds at lower resolutions.

TABLE 5. Regional averages of band emissivities retrieved from day/night MAS data at different resolutions.

resolution (m)	band 30 3.745μm	band 31 3.905μm	band 32 4.064μm	band 42 8.467μm	band 45 10.975μm	band 46 11.969μm	band 48 13.274μm
100	0.958	0.968	0.972	0.918	0.957	0.954	0.969
200	0.963	0.972	0.974	0.917	0.958	0.956	0.970
400	0.966	0.974	0.975	0.918	0.959	0.957	0.970
800	0.967	0.975	0.976	0.918	0.960	0.958	0.970
1600	0.970	0.977	0.976	0.918	0.961	0.959	0.970
3200	0.967	0.978	0.976	0.916	0.959	0.957	0.970
maximum differences at all resolutions							
	0.012	0.010	0.004	0.002	0.004	0.005	0.001

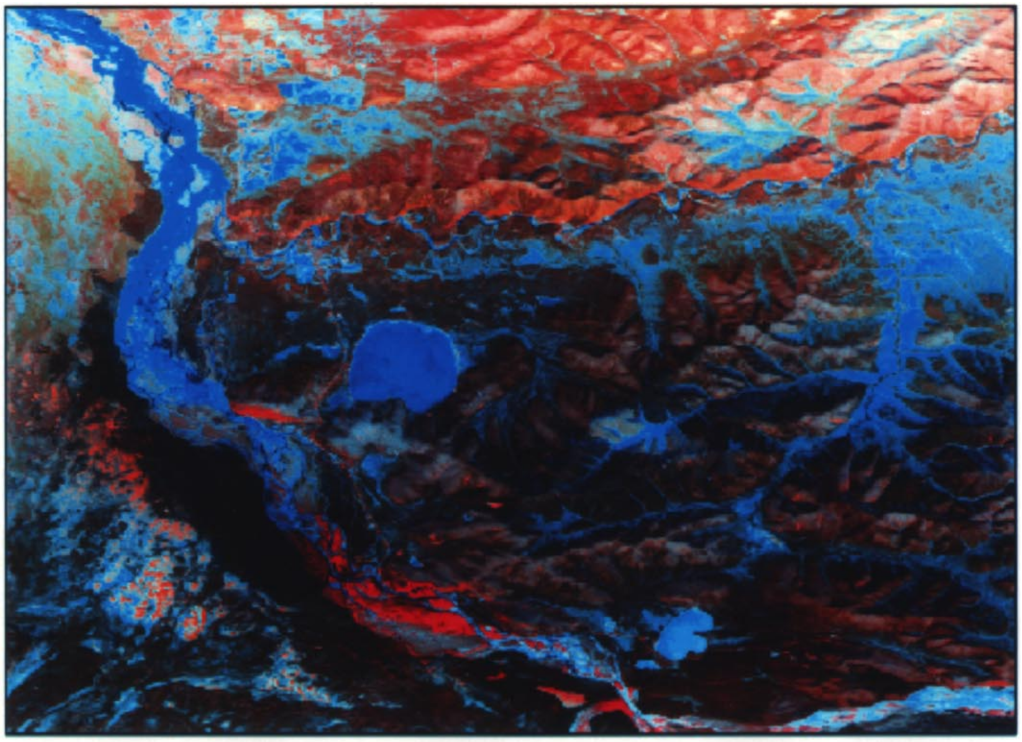
Note: The retrieved emissivity in band 42 is lower than expected. This is an area for improvements of the thin cirrus model used in the day/night LST algorithm.

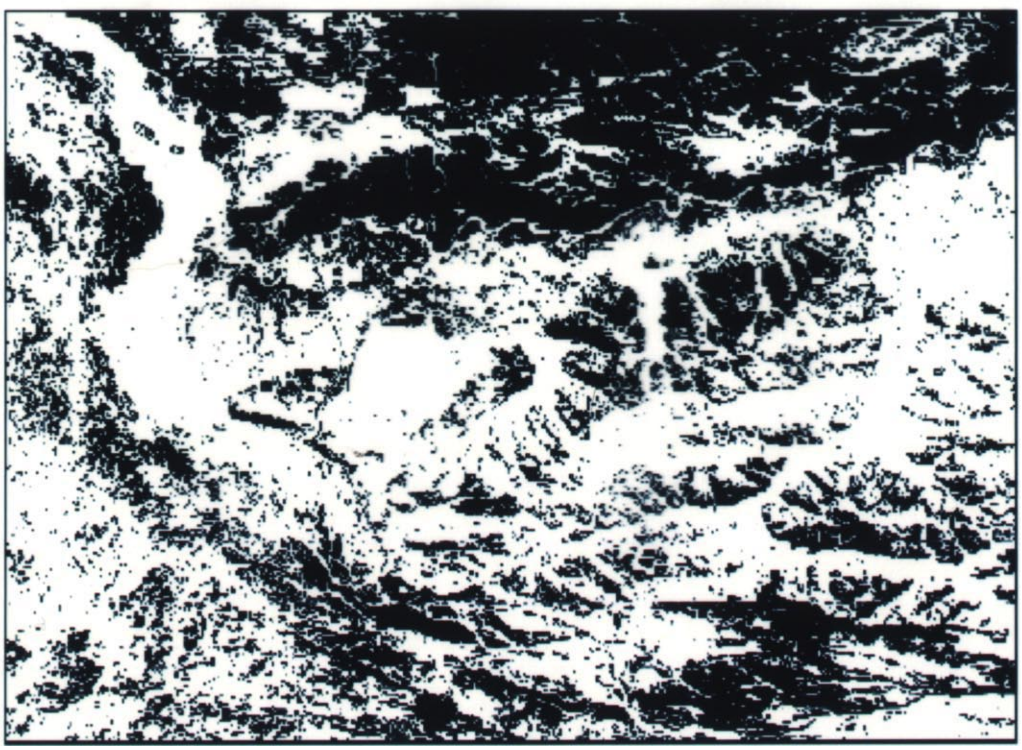
Snow Cover (MOD10)

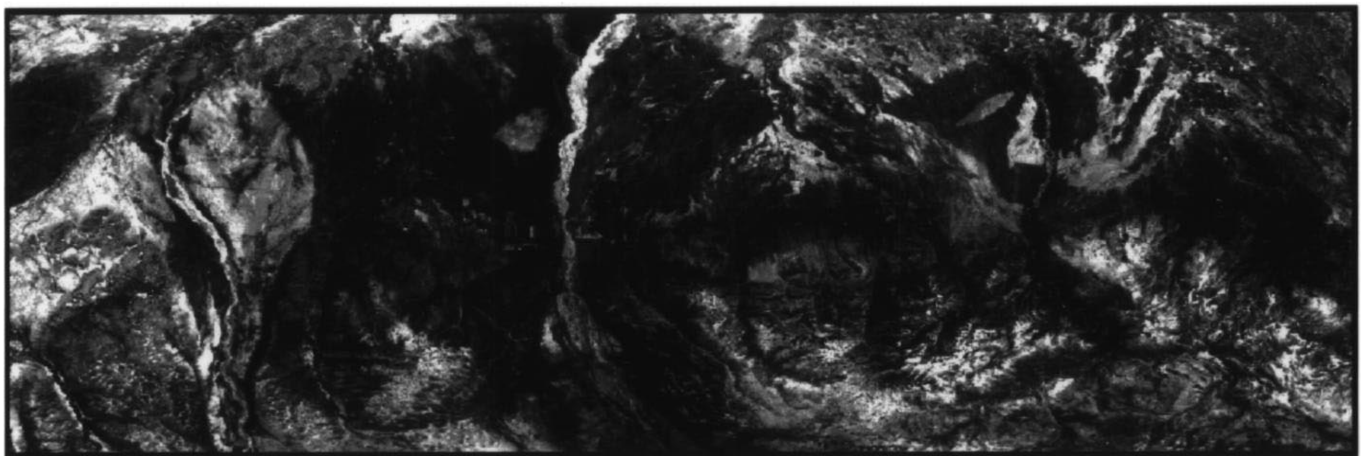
- Objective:
  - Map the spatial and temporal extent and variability of snow cover for input to regional-scale hydrologic models and GCMs
- Features:
  - Uses modified SNOMAP algorithm with inputs from MODIS VNIR and SWIR bands (MOD09R)
  - Masked for clouds, oceans, large lakes
  - Daily clear-sky Level 2 product
  - Level 3 gridded product on daily and 8-day composite interval also available
  - Postlaunch global daily snow albedo maps are also planned

Demonstration of SNOMAP Algorithm

- Prototype
  - Harding Lake, Alaska, April 6, 1995
  - MODIS Airborne Simulator (MAS) data
  - Snow mapped using SNOMAP algorithm
  - Does quite well even in topographically shaded areas
  - Snow-free road can be easily seen in snow map image
  - Snow under dense trees is problematic
- Error Estimates
  - Land cover-type dependent; generally 5%, up to 15% in forests
  - Snow cover errors will average 8 – 10% for NA and Eurasia in winter; less in summer







MAS Channel 1

Vegetation Density

Snow Map

13 April 1995

Enhanced SNOMAP Algorithm

- Snow Detection Algorithm
  - Uses Normalized Difference Snow Index: (B4-B6) / (B4+B6) >0.40;
  - Threshold of >11% reflectance in B2 (NIR); >10% in B4
  - Enhancement lowers NDSI threshold of 0.40 by using NDVI according to canopy reflectance model simulations
    - Allows mapping of snow in pixels >50% covered by vegetation
- Results—Central Alaska
  - Snow-covered scene of diverse vegetation covers

		Vegetation Density	
Method		<50%	"50%
Original	96%	71%	
Enhanced		98%	99%

  - Enhanced algorithm greatly improves mapping of snow in forests

Enhanced SNOMAP Accuracy Projections

- Projecting Global Accuracy
  - Accuracy depends on land cover type

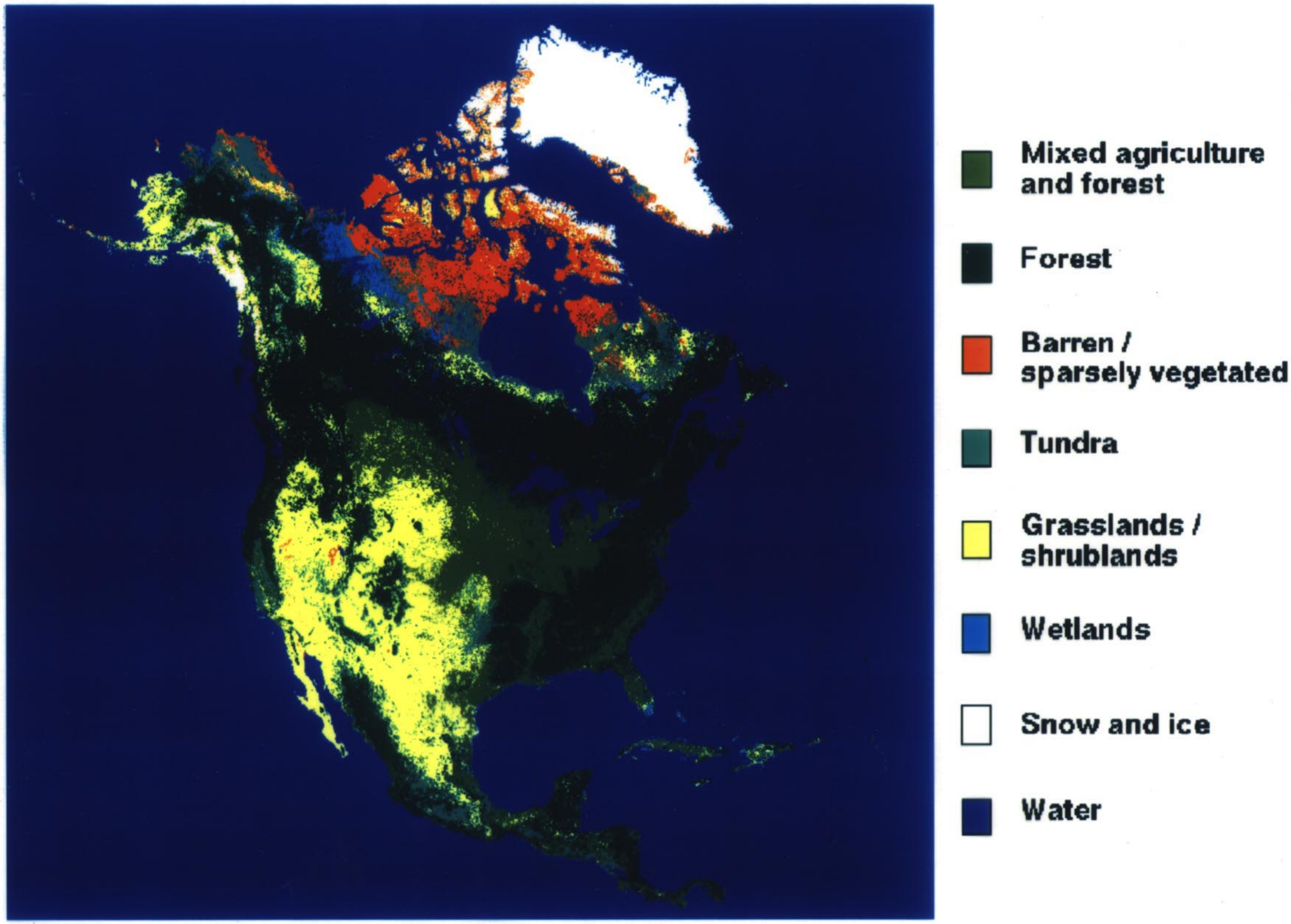
Land Cover Type	Errors (%)
Forests	15
Mixed agriculture and forest	10
Barren/sparsely vegetated	5
Tundra	5
Grassland/shrubland	5
Wetlands	5
Snow/ice	5

  - Estimates are based on MAS surveys in 1993, 1994, 1995

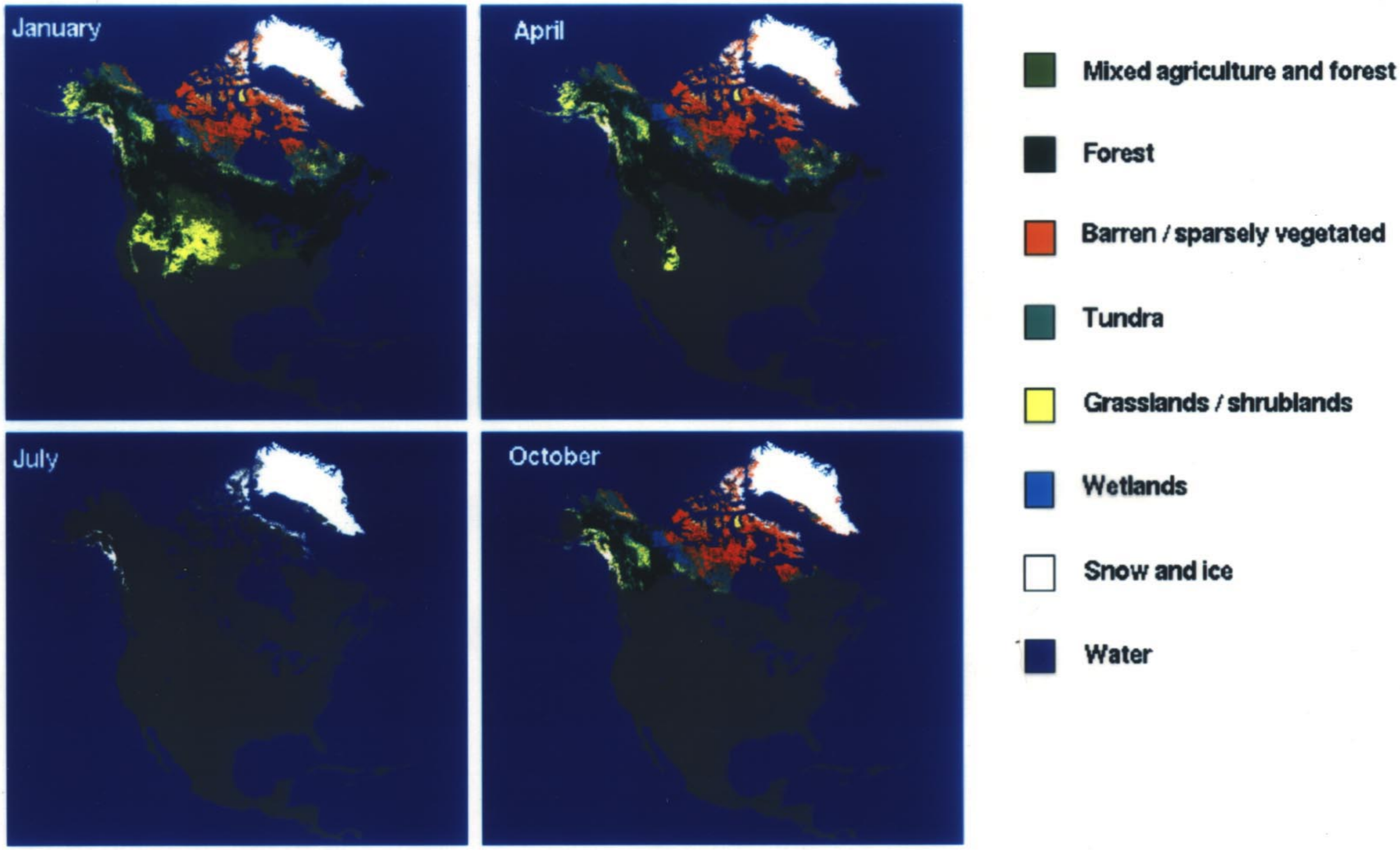
Land Cover for SNOMAP Errors

- Projecting Global Accuracy, Cont.
  - Accuracy also depends on proportions of land cover types
  - Land Cover Type Maps for continents, regions
    - IGBP 17-class map from 1-km AVHRR data remapped into eight broad classes
    - Areal proportions determined above snow line in each month
    - Global accuracy estimate obtained by area-weighted averages of class accuracies
- Overall Estimate (North America and Eurasia)
  - Error rate at about 8 percent; i.e., 92 percent accurate

North America Land Cover



North America



Estimated errors (in %) in snow mapping using EOS/MODIS data

Month	North America	Eurasia
January	9	9
February	9	9
March	9	10
April	9	10
May	6	8
June	5	6
July	5	5
August	5	5
September	5	5
October	6	7
November	9	8
December	9	8

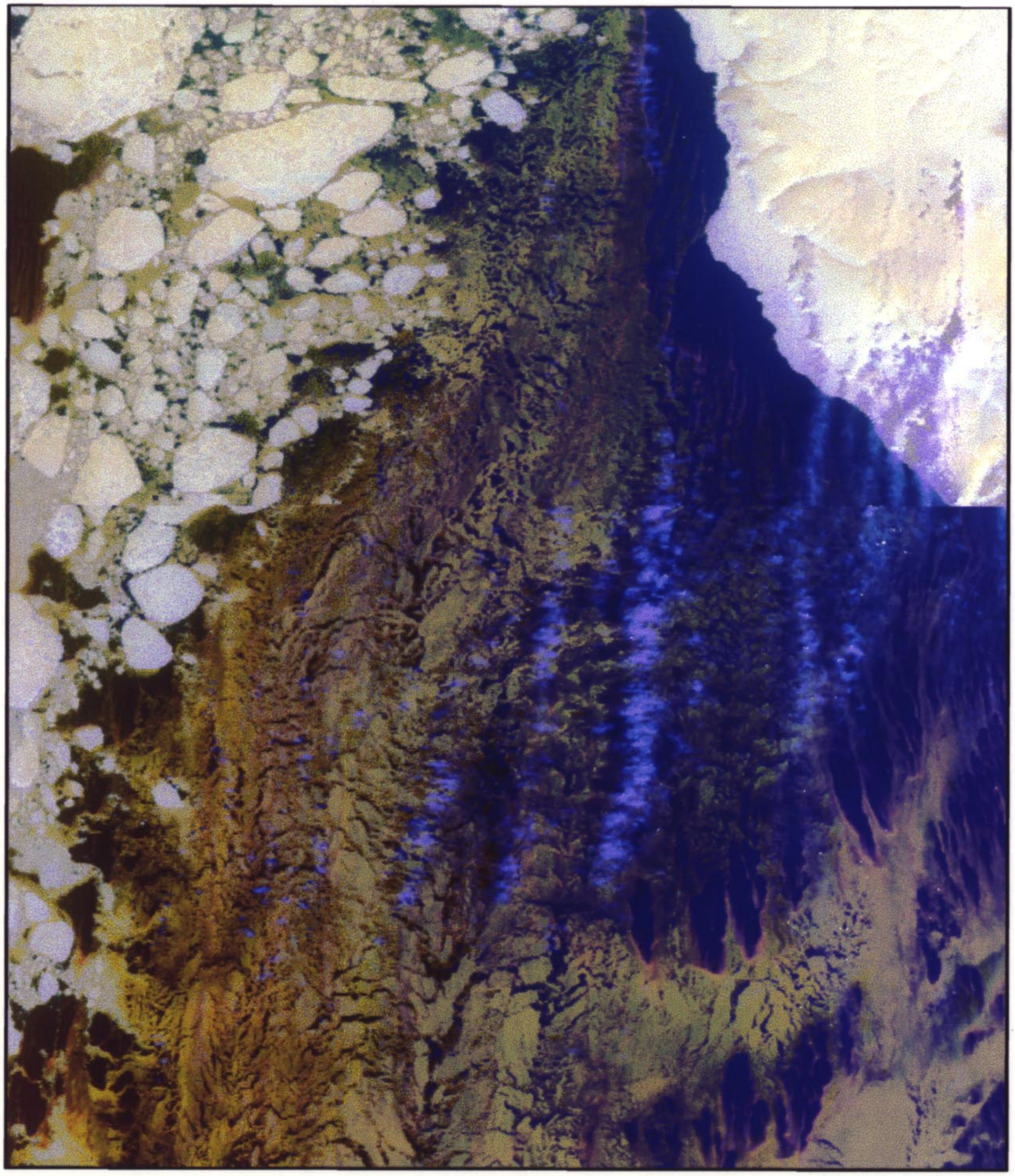
4.010

Sea Ice

- Objective:
  - Categorize and map sea ice using MODIS bands
- Features:
  - Sea ice extent and generalized type of sea ice are identified using reflective characteristics and ice surface temperature
  - Masked for clouds
  - Daily clear-sky Level 2 product on polar grid
  - Level 3 gridded product on daily and 8-day composite interval also available

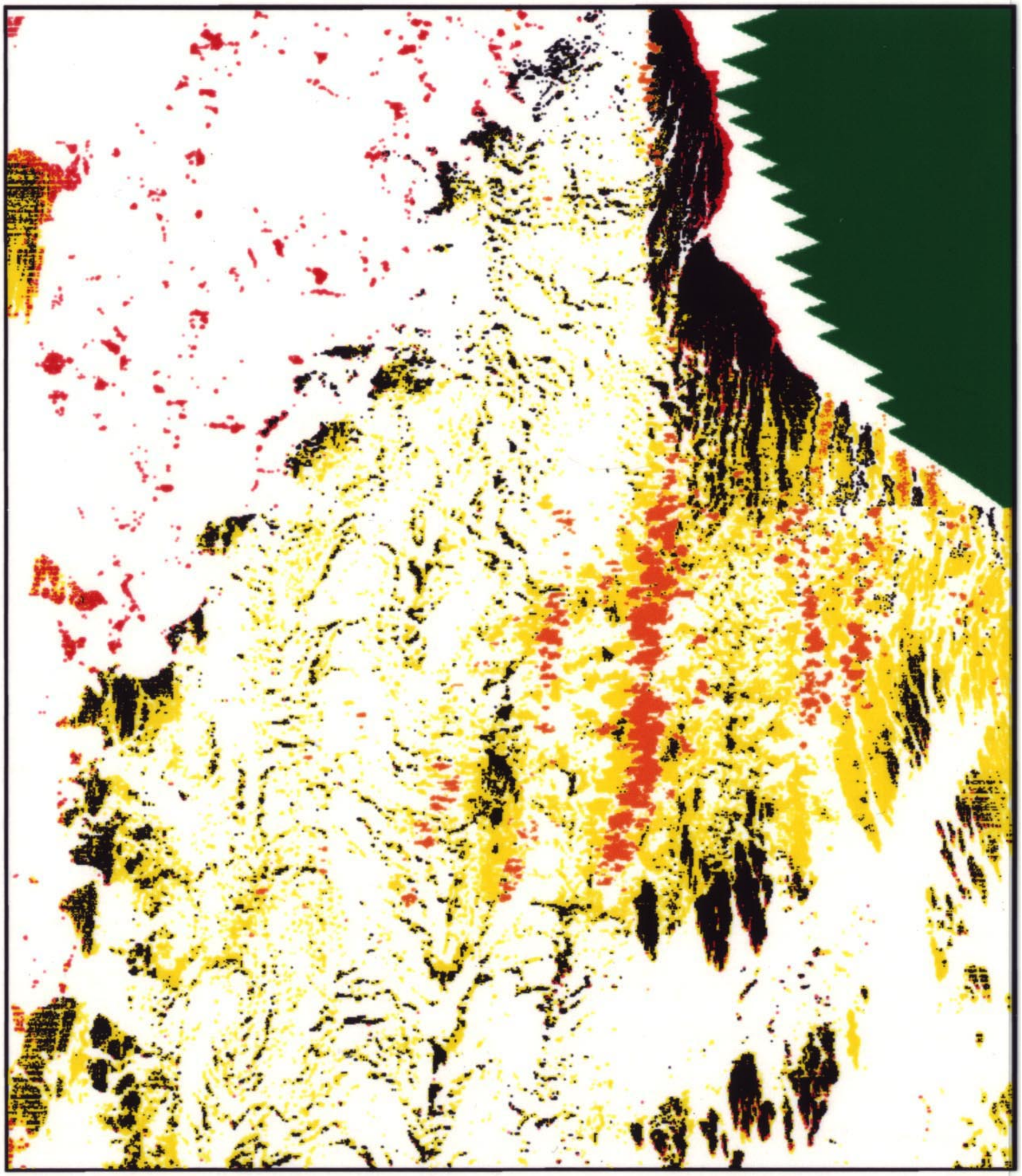
Sea Ice Algorithm

- Identification of Sea Ice
  - By reflectance
    - Uses Normalized Difference Snow Index (NDSI) > 0.40 and visible reflectance (0.55 μm) > 0.17 to differentiate (snow-covered) ice from water
    - Reflectance signatures used to identify new sea ice and snow-covered sea ice
  - By Ice Surface Temperature (IST)
    - Estimated from split-window technique after Key et al. (1997)
    - Separation of open water, new ice, young ice, first-year ice from IST
  - Cloud identification
    - Uses brightness temperature test difference for 11 and 4 μm bands



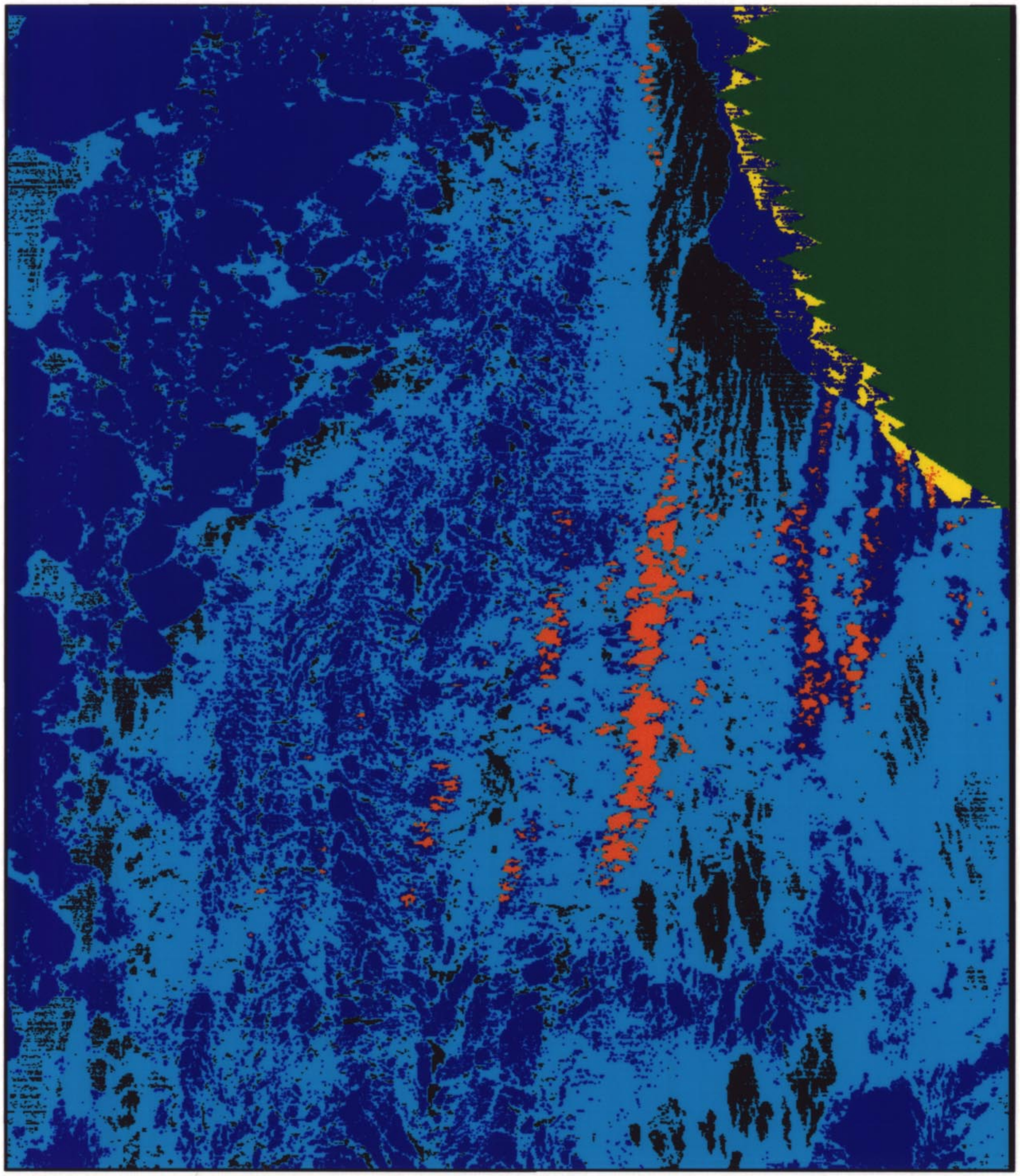
MAS image acquired 8 April 1995 near St. Lawrence Island in Bering Sea. Color (RGB) image created with MAS channels 1 (0.55 um), 7 (0.87 um), 10 (1.6 um). Ice flow around St. Lawrence Island its polynya are observed.

G. Riggs (RDC/GSFC) and D. Hall (GSFC)



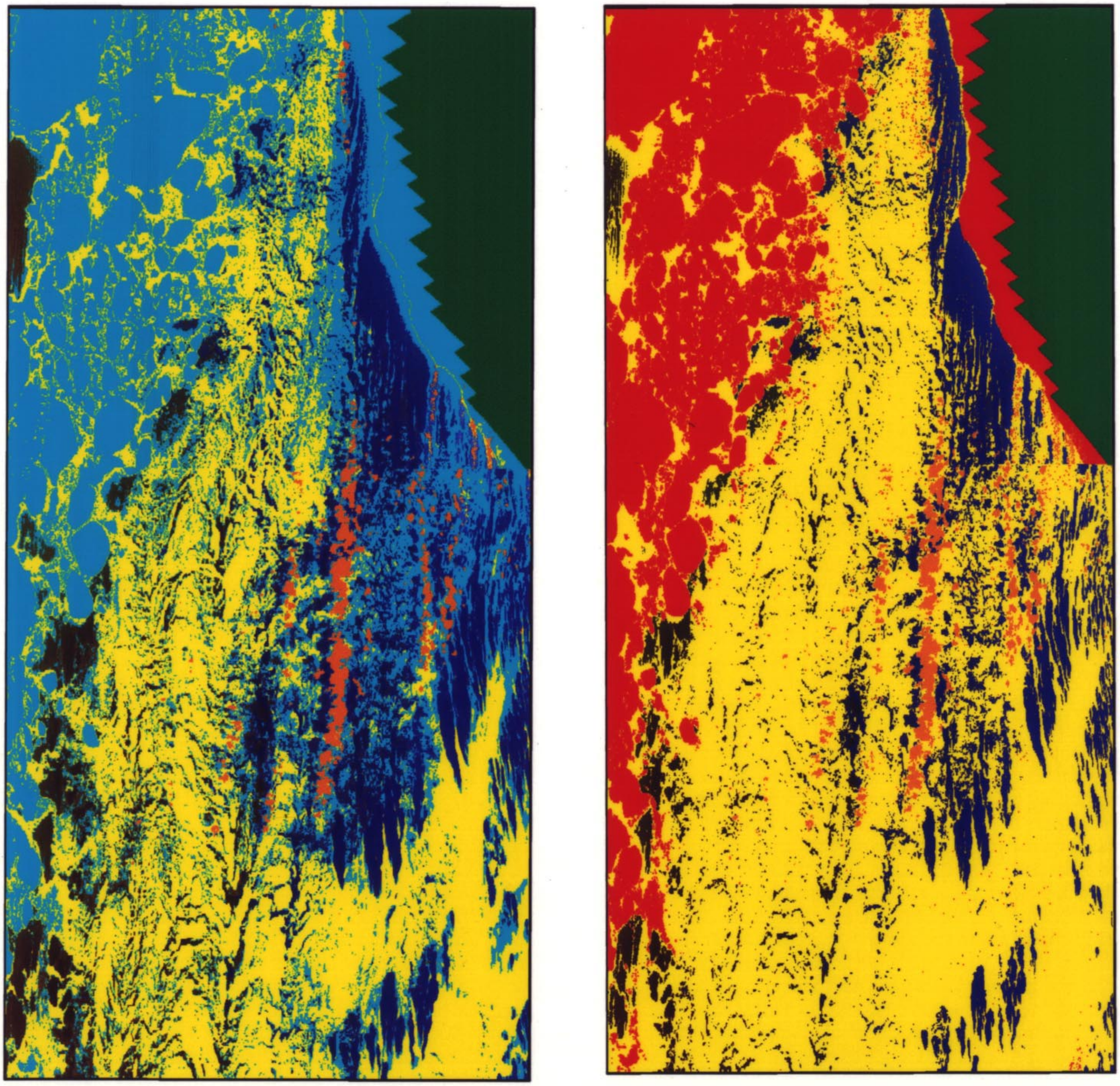
Combined reflective and IST sea ice map. Sea ice identified by both reflectance and IST (white), sea ice identified by IST only (yellow), sea ice identified by reflectance only (red). Also shown are clouds (orange) and St. Lawrence Island (green).

G. Riggs (RDC/GSFC) and D. Hall (GSFC)



Sea ice classification by ice surface temperature (IST). New ice (cyan) 271.4 K < IST<= 268 K, young ice (purple) 268 K <IST< 262 K, first-year and multiyear ice (yellow) IST <= 262. Clouds (orange) and St. Lawrence Island (green).

G. Riggs (RDC/GSFC) and D. Hall (GSFC)



Sea ice types determined with reflectance criteria tests. Left image; new ice (yellow) by reflectance threshold in 0.6 – 0.8 um region, and snow–covered sea ice by the NDSI (cyan). Right; Band ratio of MAS channel 12 (1.7 um) / channel 10 (1.6 um) identified new ice (yellow) if < 1.1, and snow–covered sea ice (red) if >= 1.1 and band 1 threshold to separate sea ice from water. Clouds (orange) and St Lawrence Island (green).

G. Riggs (RDC/GSFC) and D. Hall (GSFC)

MAS Sea Ice Prototype

- MAS Image
  - 8 April 1995 near St. Lawrence Island in Bering Sea
  - MAS channels 1 (0.55 μm), 7 (0.87 μm), 10 (1.6 μm)
  - Shows several types of ice, open water, clouds
- Sea Ice Map
  - Combines reflective and temperature tests
    - Yellow: IST only; red: reflectance only; white both; orange: cloud; green: St. Lawrence Island (1-km land mask)
- Ice Classification by Temperature
  - cyan: new ice; purple: young ice; yellow: first-year and multiyear ice
- Ice Classification by Reflectance—Two Approaches
  - New and snow-covered ice differentiated

Conclusion

- MODIS's contribution to determination of
  - Global Energy Balance
  - Local Surface Energy Balance

  will be substantial
- Land products will provide key information from
  - Surface Reflectance
  - BRDF / Albedo
  - Surface Temperature
  - Snow Cover / Sea Ice
- Prototypes demonstrate utility and suitability for radiation budget studies