Surface Temperature and Melt on the Greenland Ice Sheet, 2000 – 2011

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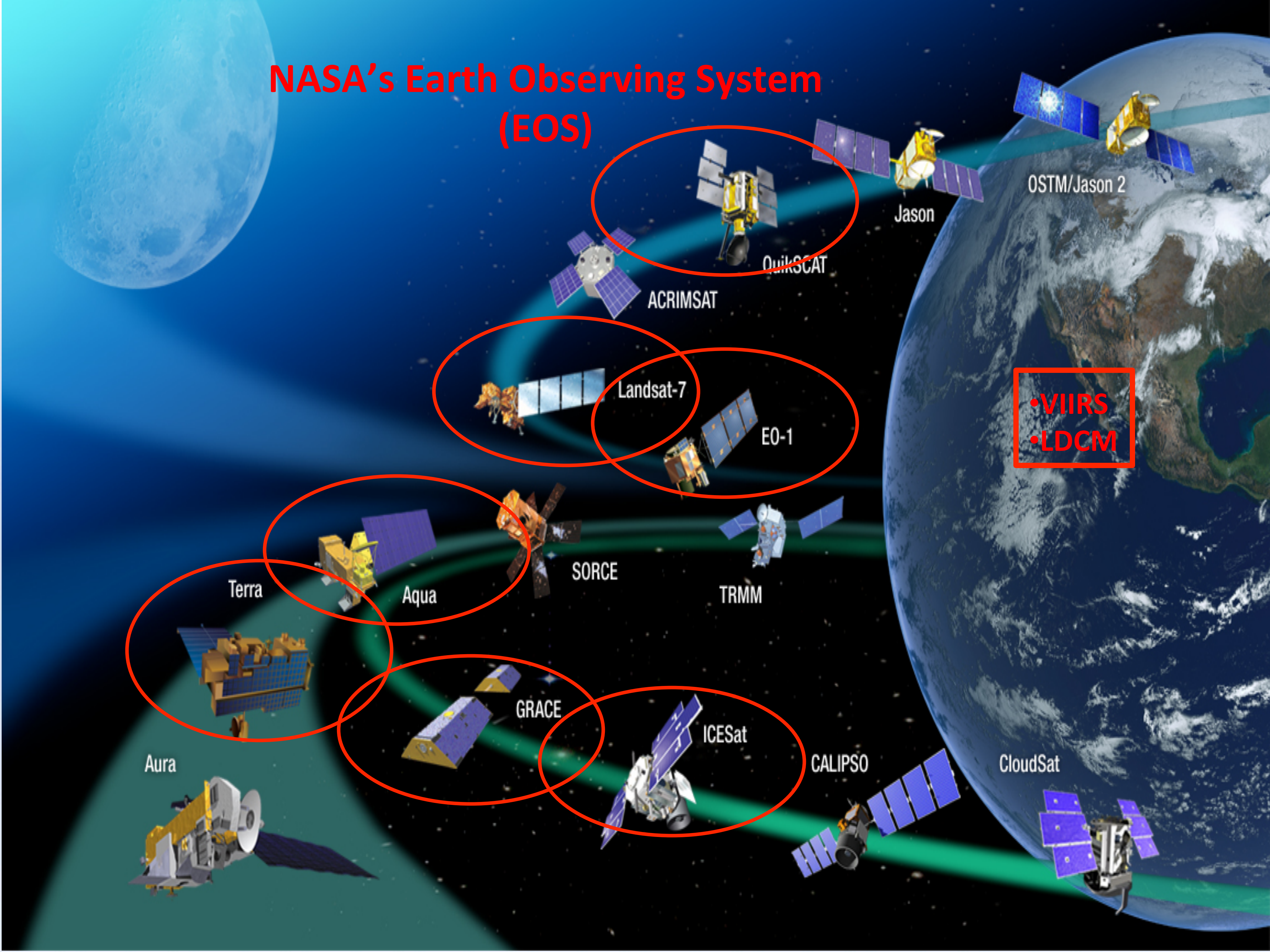
Outline

- Introduction to the Cryosphere
- Climate warming at high latitudes
- Greenland surface temperature and melt from MODIS


NASA's Earth Observing System
(EOS)
OSTM/Jason 2
Jason
QuikSCAT
ACRIMSAT
Landsat-7
EO-1
•VIIRS
•LDCM
SORCE
TRMM
Terra
Aqua
GRACE
ICESat
CALIPSO
CloudSat
Aura

The Cryosphere

- Seasonal snow cover
- Mountain glaciers
- Ice sheets
- Frozen lakes
- Sea ice
- Permafrost

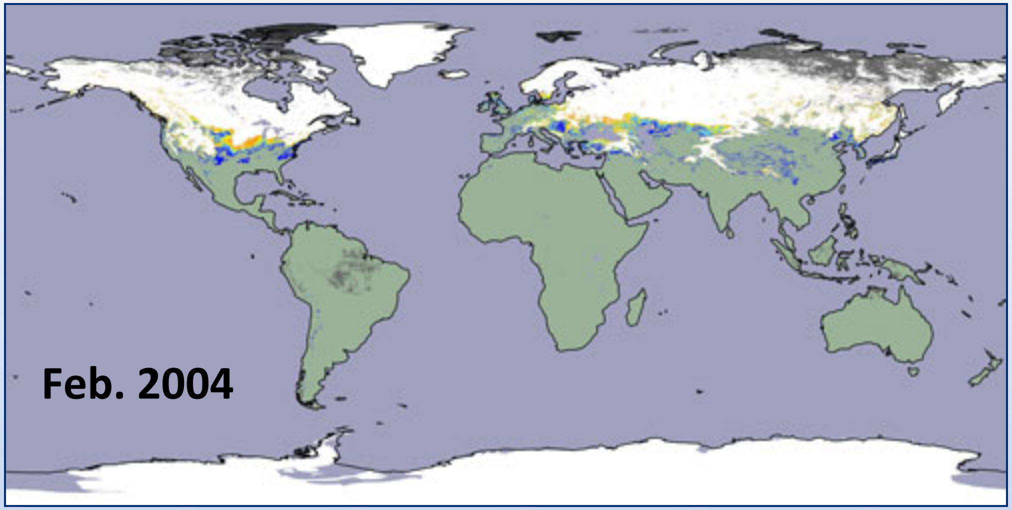
NASA Visible Earth

Evidence of Climate Warming has been Dramatic in the High Latitudes of the Northern Hemisphere

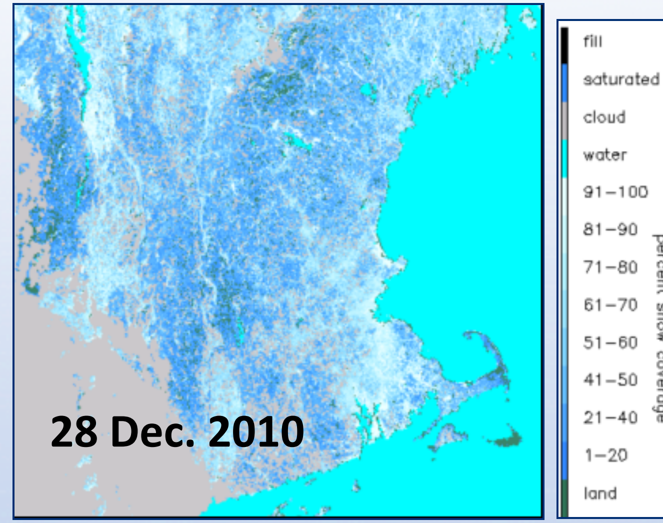
- In the Northern Hemisphere there has been a decrease in:
  - Duration of lake ice over the last 150 years
  - Extent of sea ice since 1979
  - Extent of snow cover since 1966
- Permafrost is warming and thawing in many areas
- Small glaciers are shrinking (globally)
- Melt on the Greenland Ice Sheet has been accelerating


Seasonal Snow Cover

Satellite Snow-Cover Products

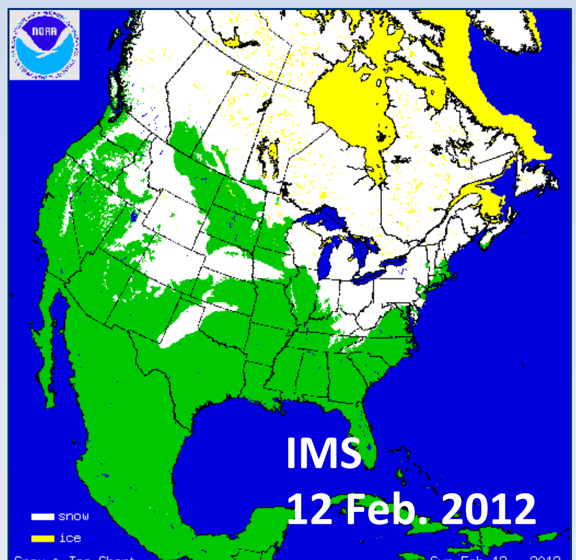


MODIS monthly snow-cover map

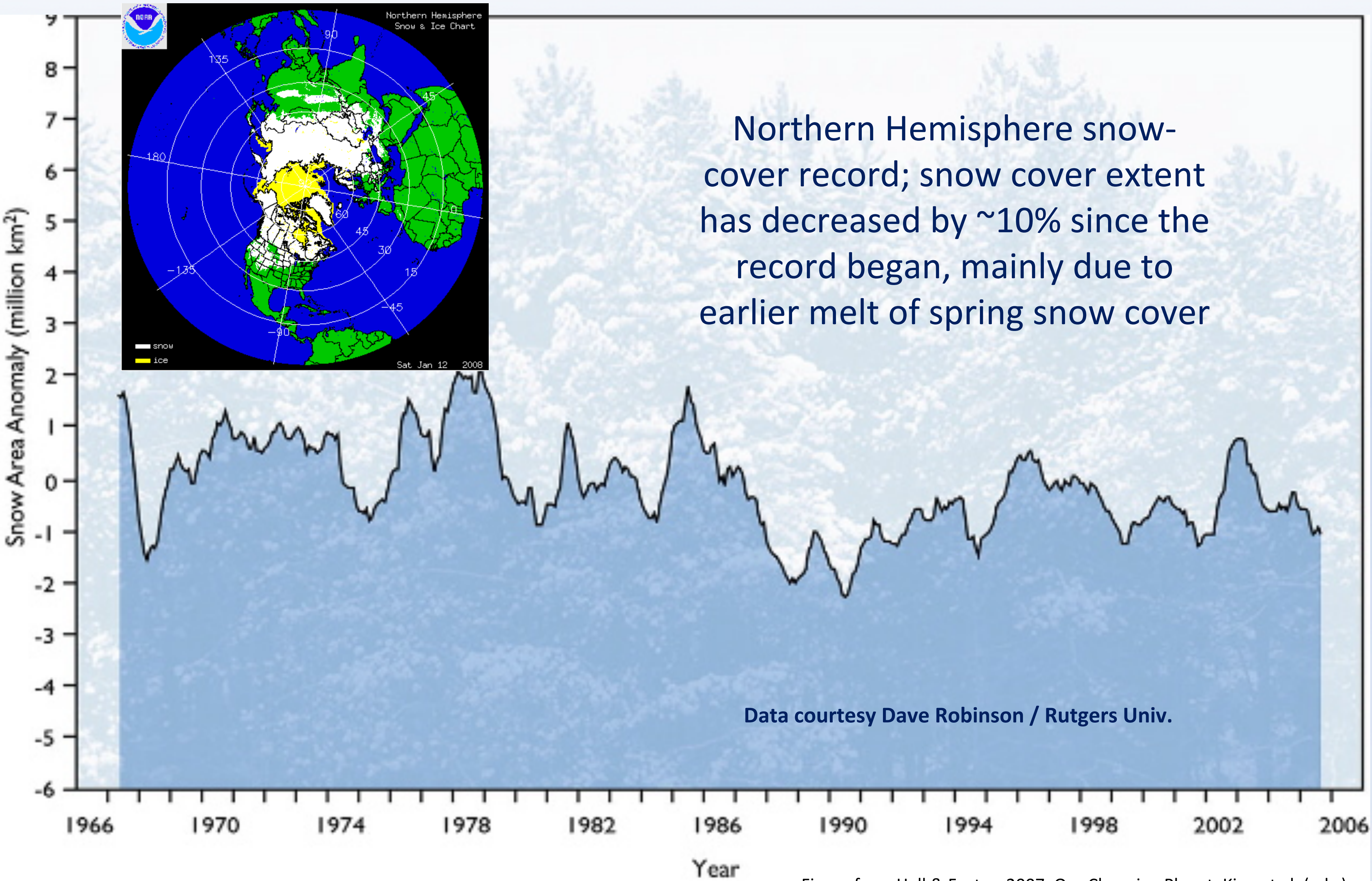


Northeastern U.S. MODIS swath fractional snow-cover map

National Ice Center (NIC) snow-cover map



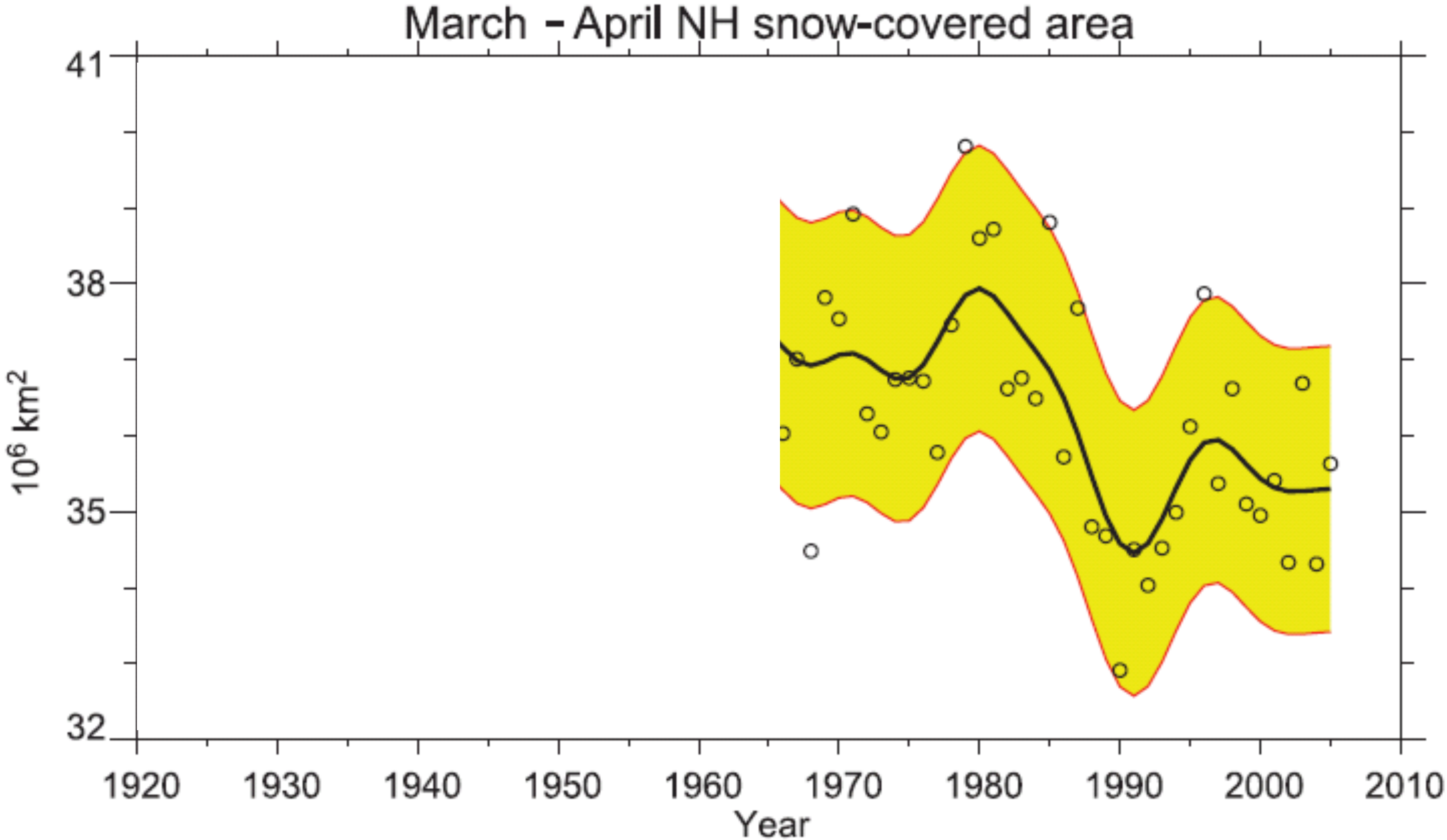
Northern Hemisphere Snow Cover Anomalies – Departure from 30-year Mean



Northern Hemisphere snow-cover record; snow cover extent has decreased by ~10% since the record began, mainly due to earlier melt of spring snow cover

Data courtesy Dave Robinson / Rutgers Univ.

Figure from Hall & Foster, 2007, Our Changing Planet, King et al. (eds.)



Snow-covered area derived from station data (before 1972) and NOAA satellite data (after 1972); the smooth curve shows decadal variations (updated from Brown, 2000)

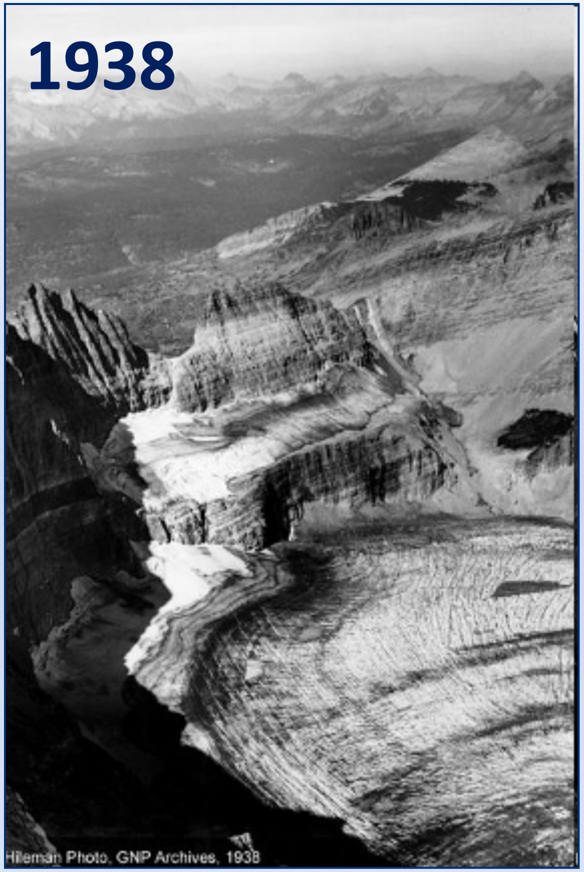
Small Glaciers and Ice Caps have been Shrinking

Globally, glaciers have been receding since ~1850; recession has accelerated in the last quarter century

Photo by Kimberly Casey/NASA

Glacier National Park, Montana

Grinnell Glacier Recession*



T.J. Hileman

Carl Key (USGS)

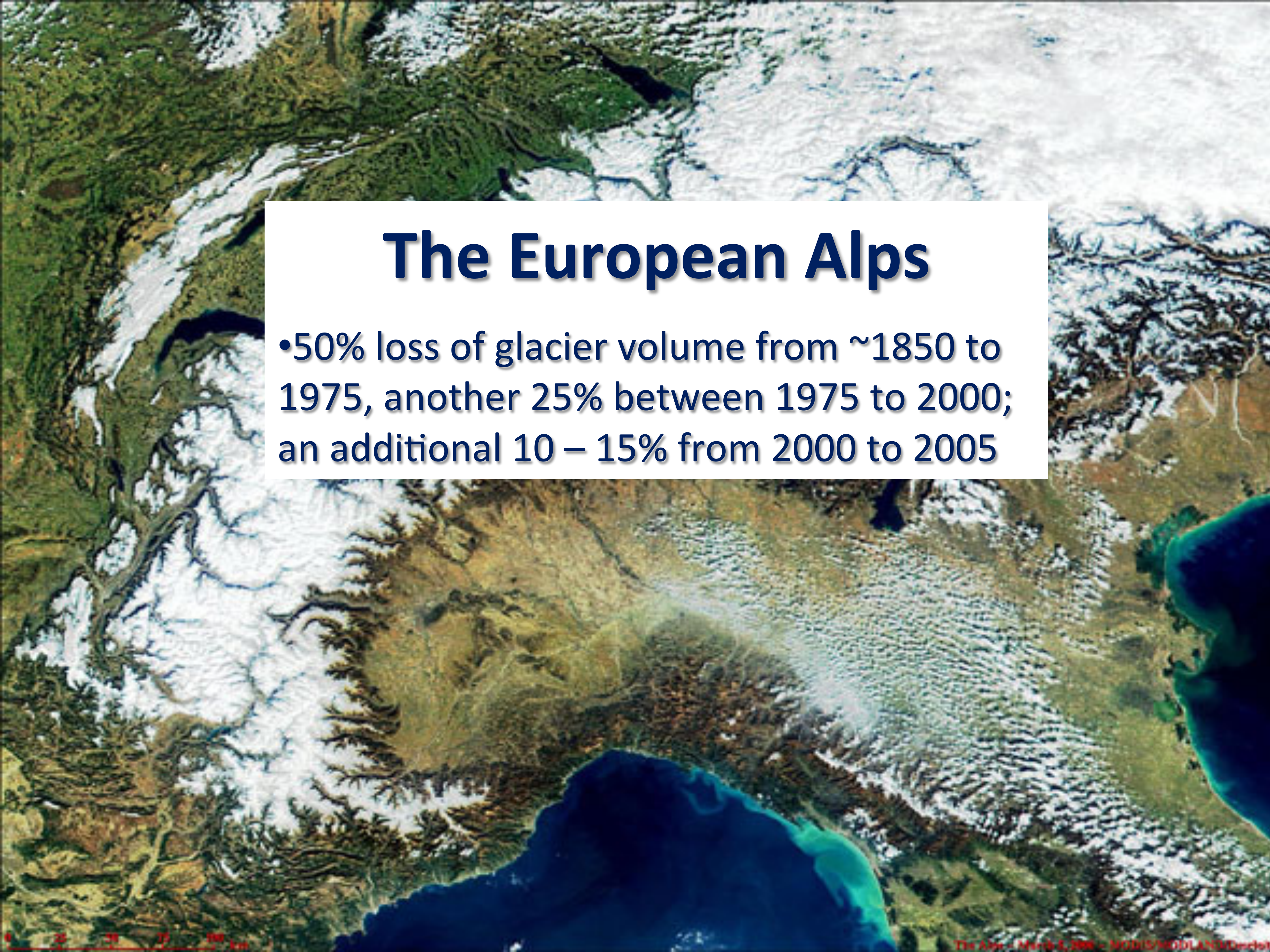
Blase Reardon (USGS)

Since 1900 there has been an increase of ~1°C average summer temperature

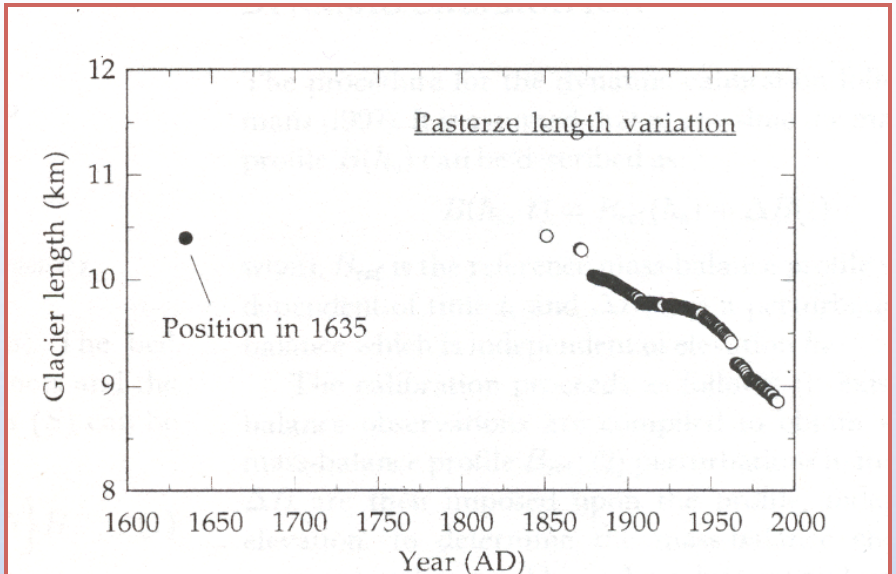
***Not all of the glaciers in GNP are retreating at this high rate**

The European Alps

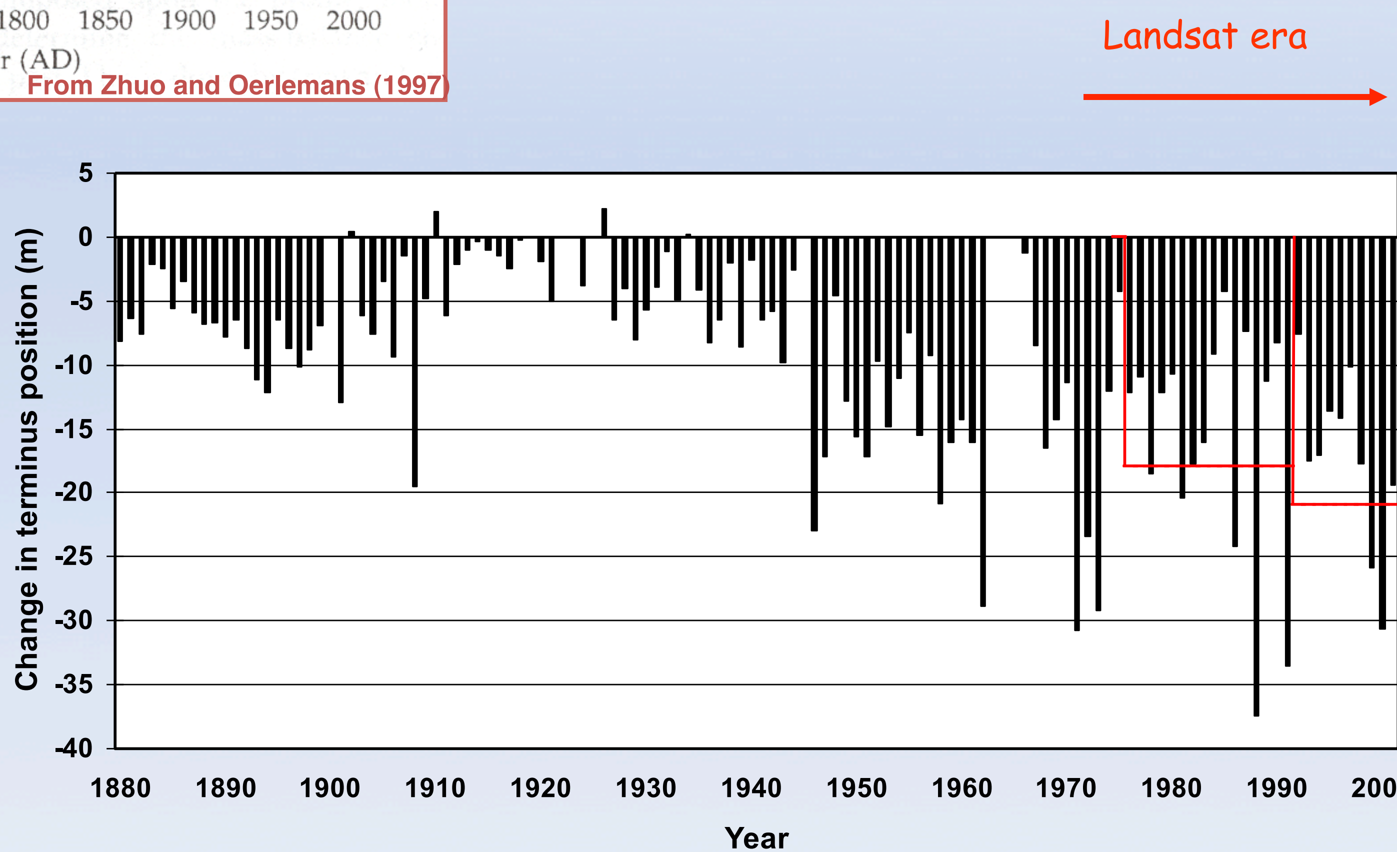
- 50% loss of glacier volume from ~1850 to 1975, another 25% between 1975 to 2000; an additional 10 – 15% from 2000 to 2005



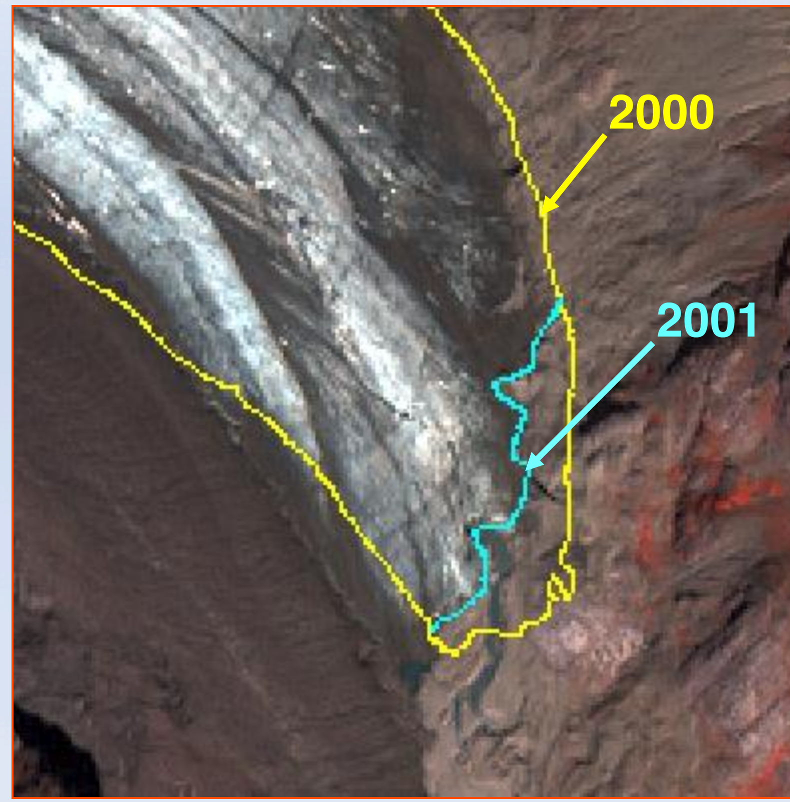
Historical Length Variations of the Pasterze Glacier, Austria



From Zhuo and Oerlemans (1997)



4-m resolution Ikonos image of the Pasterze Glacier in 2001

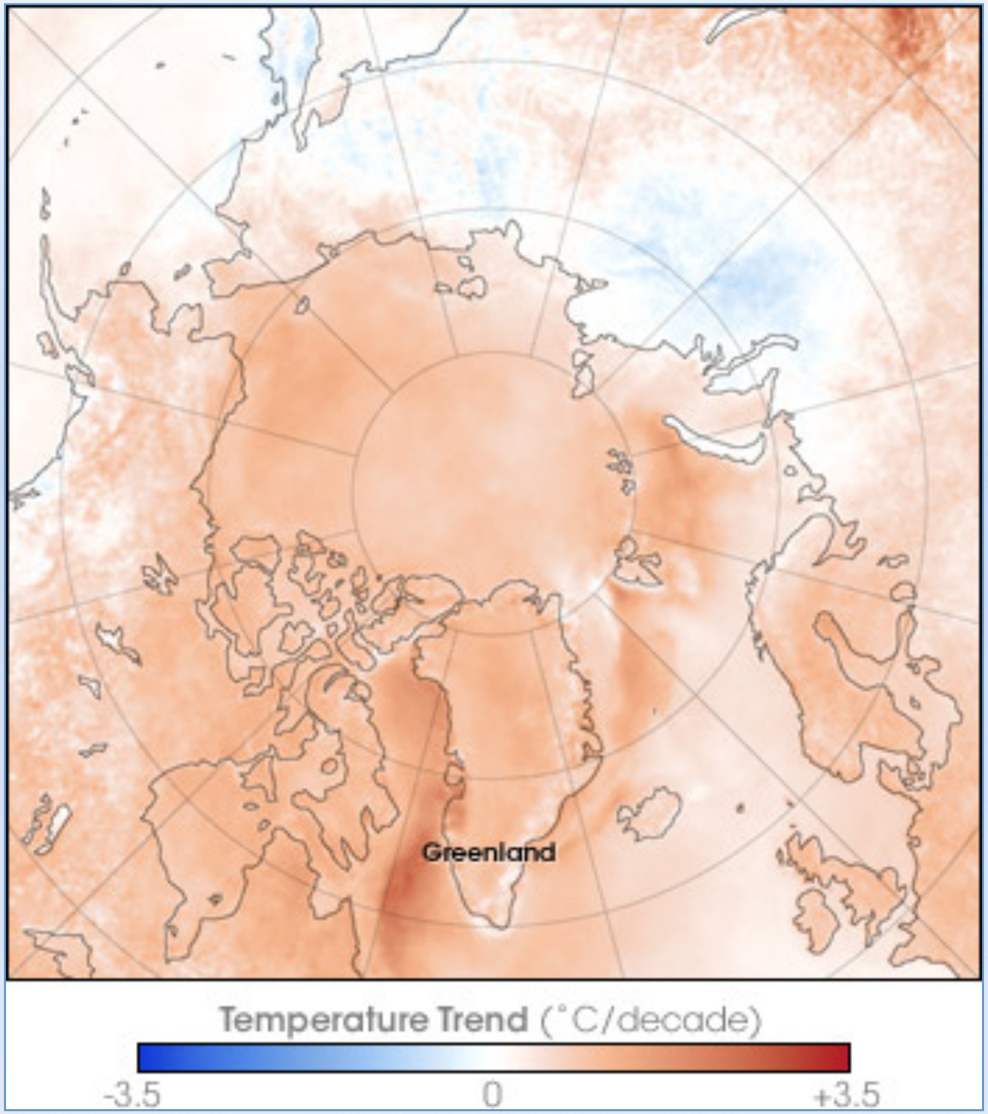


22,096±46m^2 decrease in area of the terminus

From Hall et al., 2003

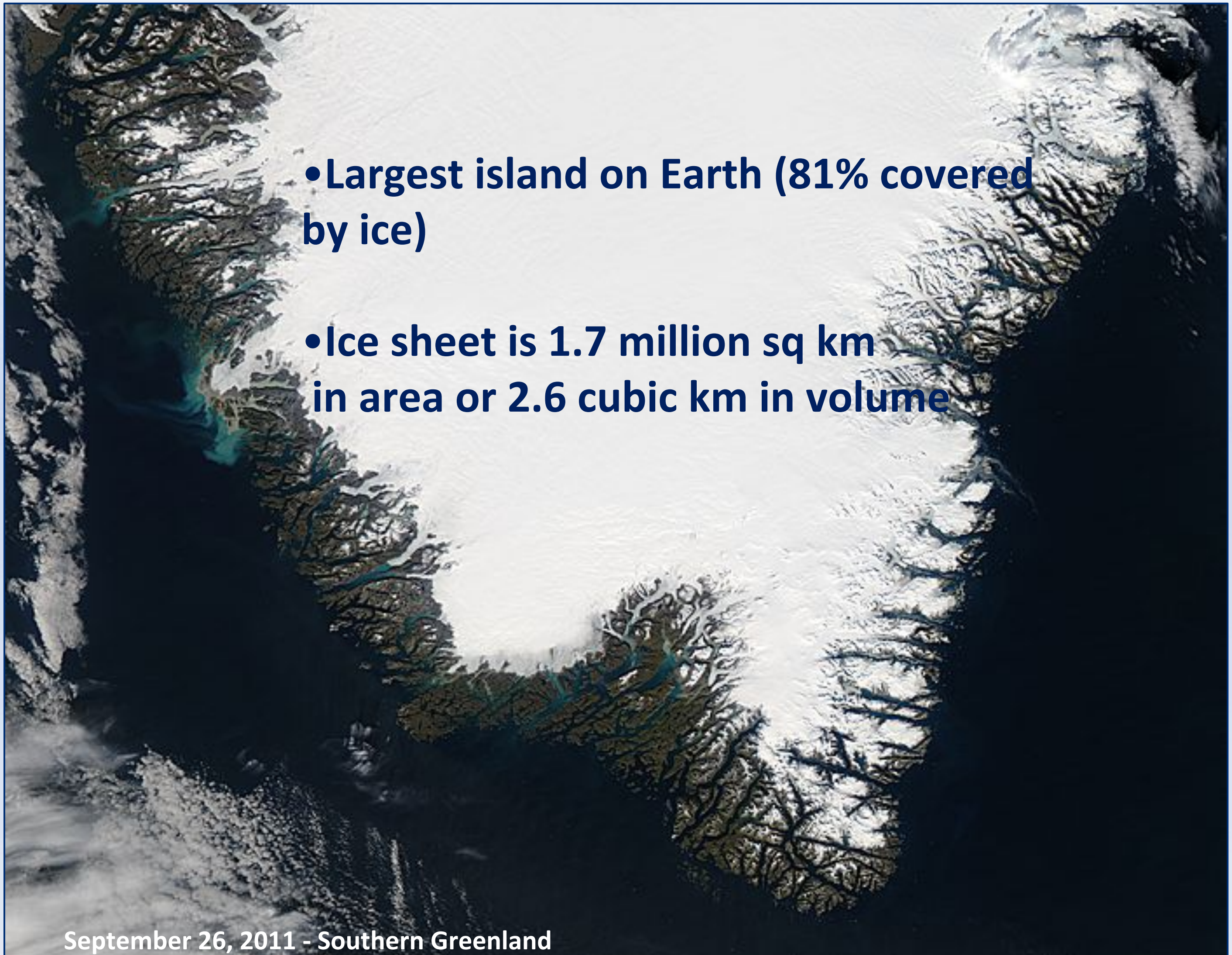
AVHRR IR satellite observations show Arctic warming

The surface temperature of the Arctic above 60°N has been increasing at an average of ~0.72 ± 0.20°C per decade, from 1981 to 2007 (updated from Comiso, 2006)



http://visibleearth.nasa.gov

Greenland



- Largest island on Earth (81% covered by ice)
- Ice sheet is 1.7 million sq km in area or 2.6 cubic km in volume

September 26, 2011 - Southern Greenland

MODIS Rapid Response Team – image of the day

Contains ~8% of all of the Earth's fresh water

The ice sheet has a maximum thickness of ~3.3 km (2 mi.)

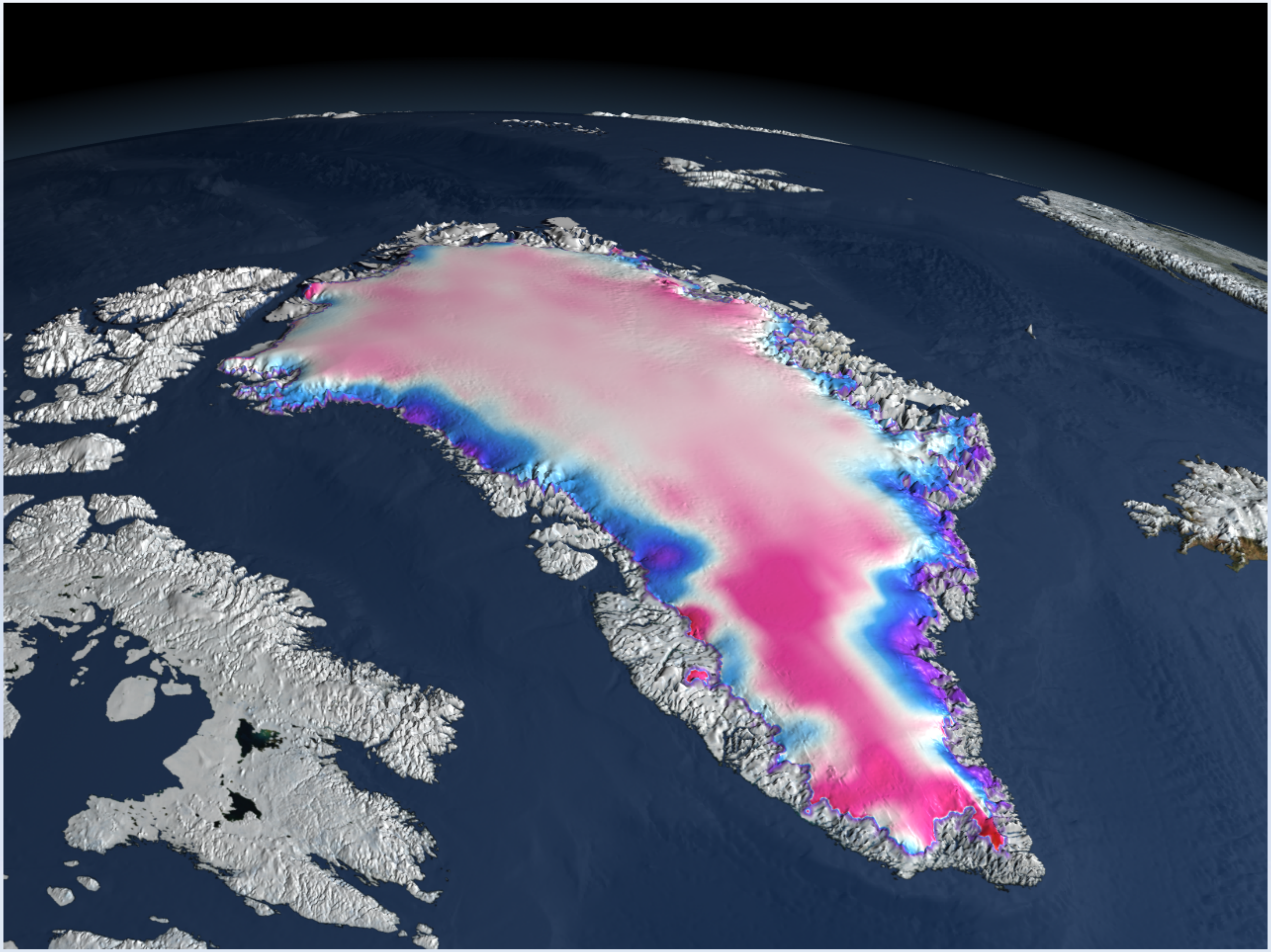
Photograph by Jason Box / OSU

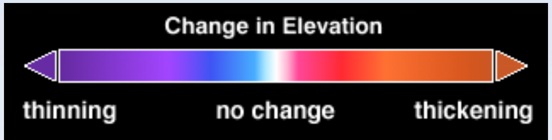
- Airborne Topographic Mapper (ATM) and ICESat laser altimetry data show greater thinning at the margins of the Greenland Ice Sheet (Krabill et al., 1999), below ~2000 m in elevation

- Rate of thinning at margins has increased from increased melting and acceleration of outlet glaciers (Zwally et al., 2011)

ICESat – Derived Changes in the Elevation of the Greenland Ice Sheet between 2003 and 2006

Increased melting and faster glacier flow lowered the surface along the margins of the ice sheet (blue), while increased snowfall thickened the ice in the interior of Greenland (pink)





http://icesat.gsfc.nasa.gov/

Increases in mass loss of the Greenland Ice Sheet have been documented in recent years using GRACE* satellite data

From 2002 to the present, GRACE gravimetry data show mass loss below 2000 m elevation, and no change (or slight gain in mass) above 2000 m

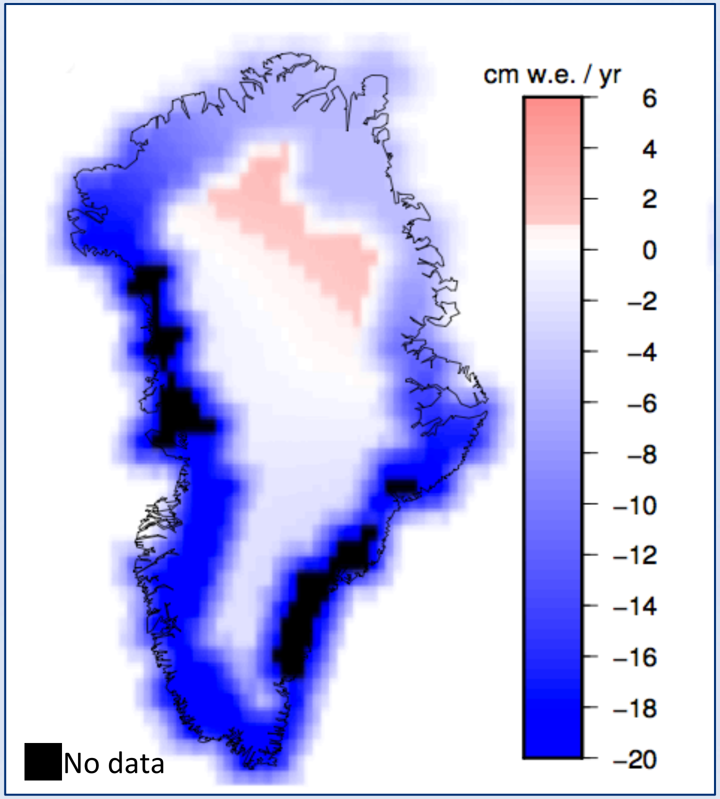
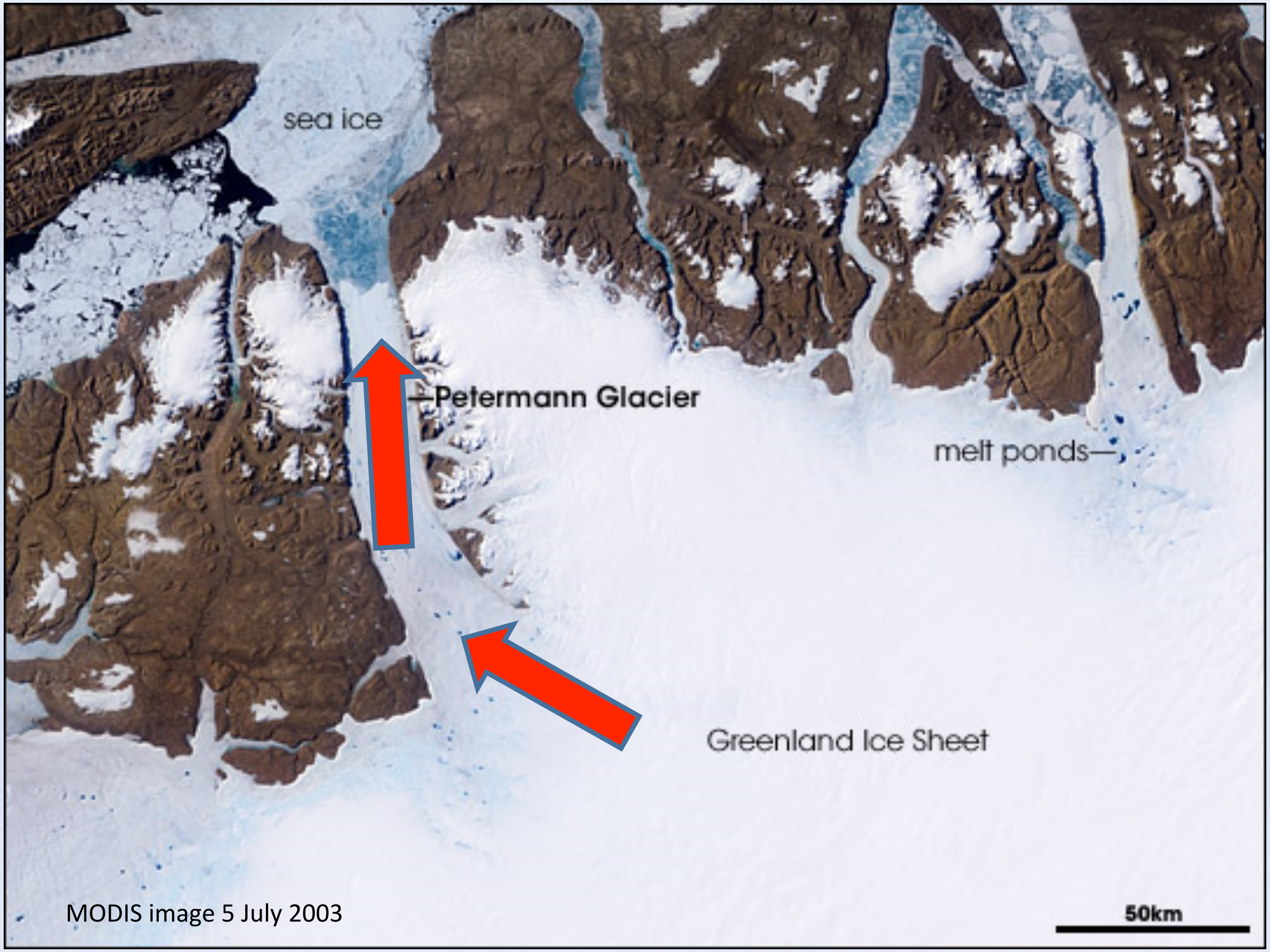


Figure courtesy of Scott Luthcke NASA/ GSFC

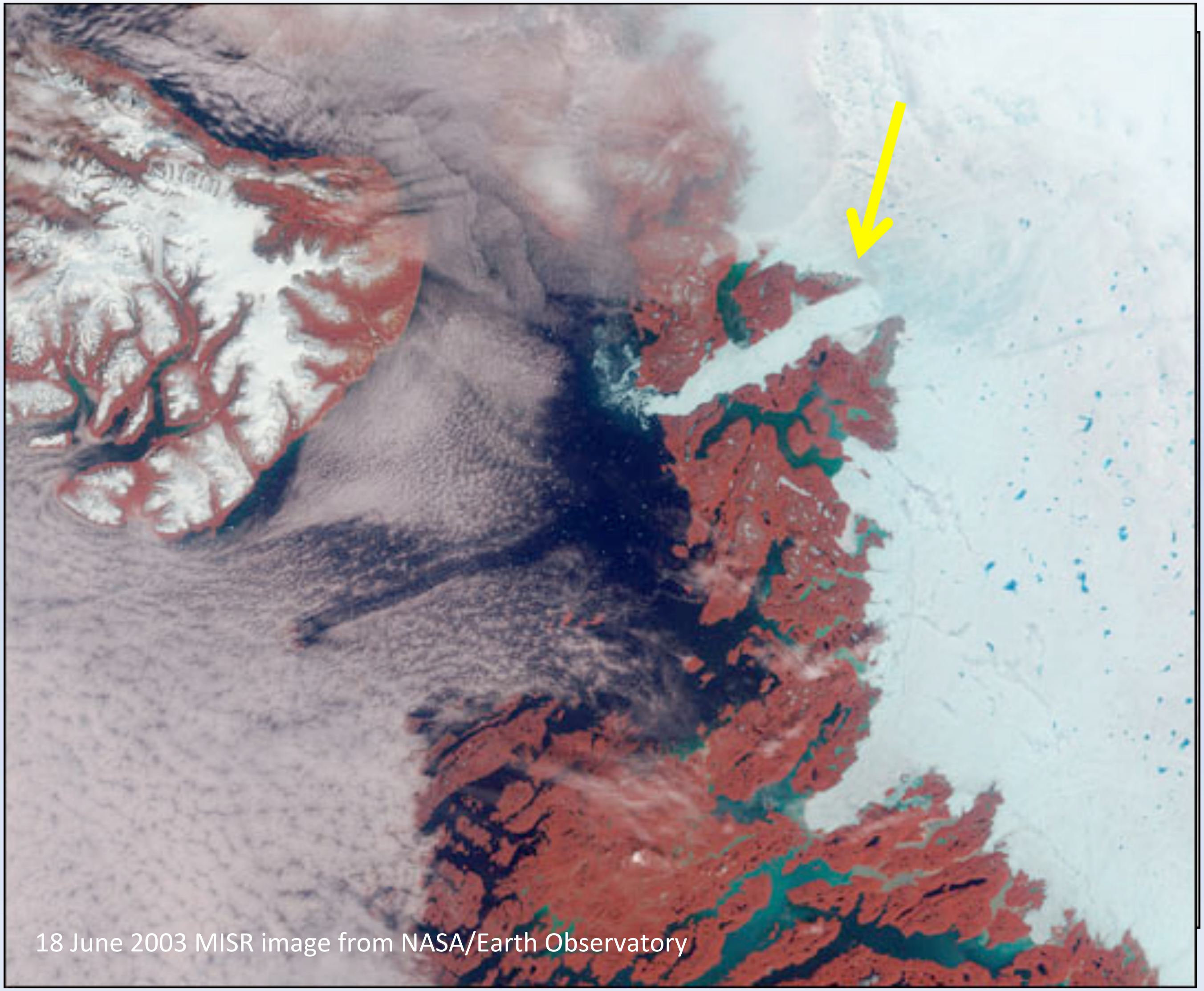
*Gravity Recovery & Climate Experiment

Emanating from the periphery of the ice sheet are many smaller ice streams and outlet glaciers that drain the main ice sheet and release icebergs into the ocean



Earth Observatory

Retreat of Jakobshavn Glacier, SW Greenland



http://earthobservatory.nasa.gov/IOTD/view.php?id=5086

NASA/USGS image courtesy of the Science Visualization Studio, at GSFC

Surface Temperature and Melt

To monitor trends in surface temperature and melt extent on the Greenland Ice Sheet

- To establish the uncertainties of mapping ice-surface temperature (IST) and surface melt extent from space

Ice Sheet Surface Temperature, or Ice-Surface Temperature (IST)

- Surface temperatures are needed to
  - Estimate radiative fluxes;
  - For input to models to calculate the ice sheet contribution to sea-level rise;

- Temperature is a physical quantity that can be compared directly with model results of skin temperature, conversely many different algorithms can be developed from the same passive- or active-MW data and they can provide different results;

- Studies disagree on the amount and rate of warming, and increases in melt extent on the Greenland Ice Sheet – knowledge of IST can help reduce those uncertainties.

MOD29 Ice-Surface Temperature (IST)

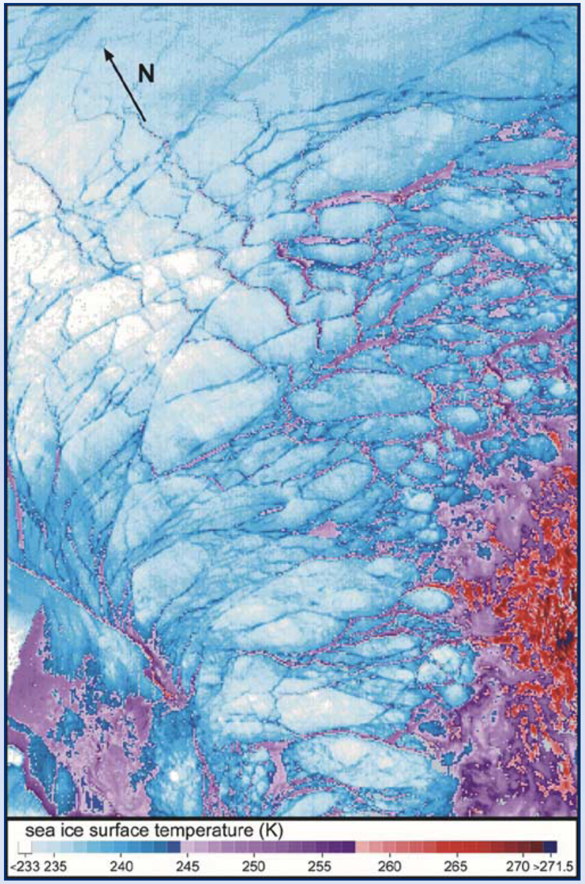
•MOD29 is the IST standard Terra MODIS data product

$$T_s = a + bT_{11} + c(T_{11} – T_{12}) + d [(T_{11} – T_{12}) (\sec θ – 1)]$$

Where T_s = surface temperature; T_{11} and T_{12} are satellite-measured surface temperatures in MODIS bands 31(11µm) and 32 (12 µm); θ is sensor scan angle and a, b, c & d are regression coefficients. Increased difference between bands 31 & 32 is related to atmospheric attenuation (Hall et al., 2004).

•This "split-window" technique is based on the Key & Haefliger (1992) and Key et al. (1997) algorithm developed for the AVHRR, but uses different coefficients for MODIS

•±1-4K accuracy (Hall et al., 2004 & Koenig and Hall, 2010)



MOD29 ice-surface temperature map of sea ice in the Arctic Ocean

MODIS:

•Land-Surface Temperature (LST), MOD11 or MYD11 (Wan et al., 2002)

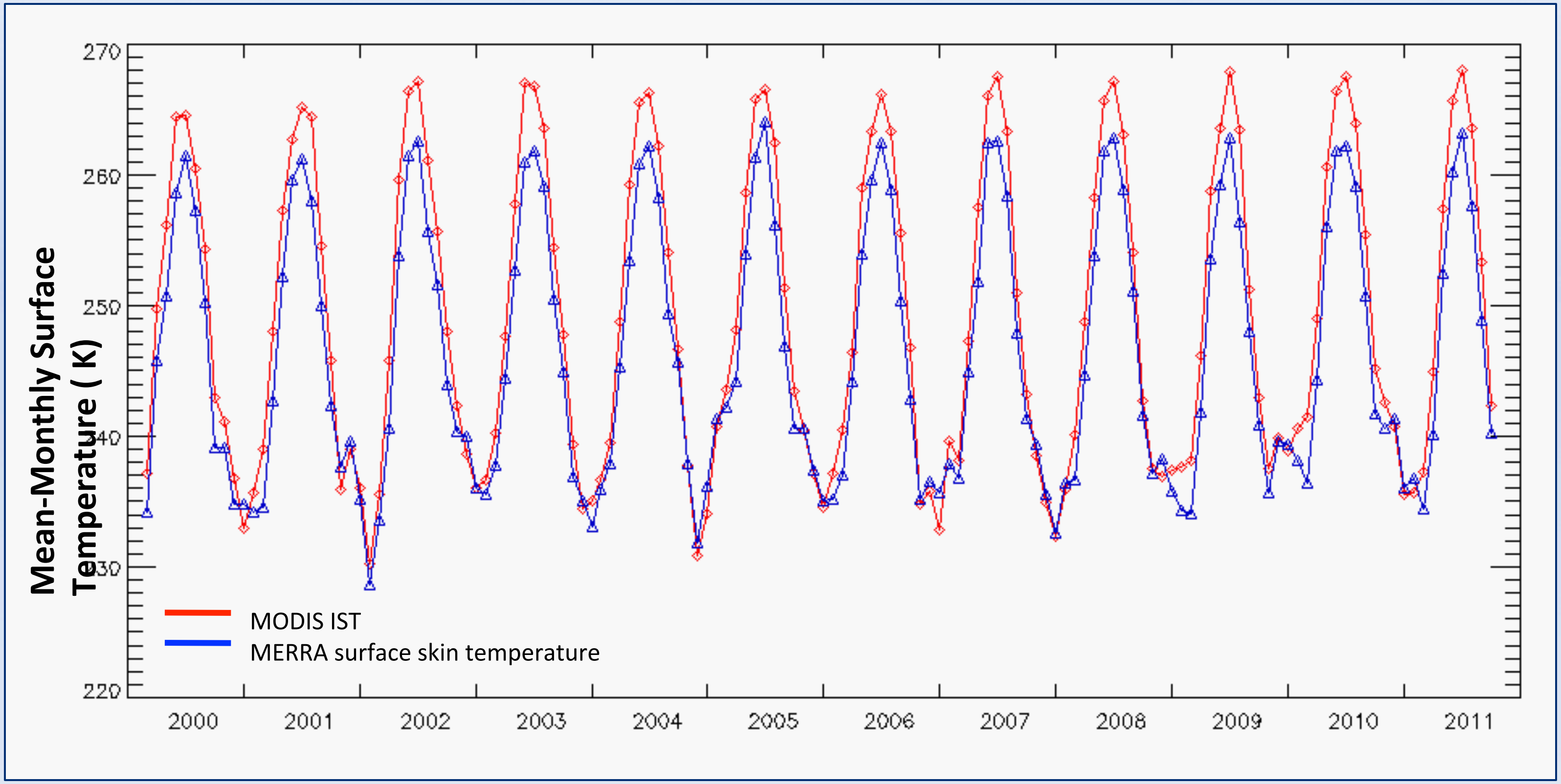
•Ice-Surface Temperature (IST), MOD29 or MYD29 (based on Key et al., 1997 algorithm initially developed for use with AVHRR)

Algorithms are similar and results compare well under winter conditions, but can diverge during the summer over the ice sheet.

MODIS Ice-Surface Temperature (IST) Environmental Science Data Record (ESDR)

- Developed an IST ESDR of the Greenland Ice Sheet using MODIS Terra and Aqua data,
    - Daily and monthly maps (downloadable online at: http://modis-snow-ice.gsfc.nasa.gov/)
    - 6.25-km spatial resolution
    - Uncertainty information in each grid cell
    - Suitable for continuation using the Visible/Infrared Imager Radiometer Suite (VIIRS)
- Studied 12-yr trends in surface temperature and melt extent, and compared with other data

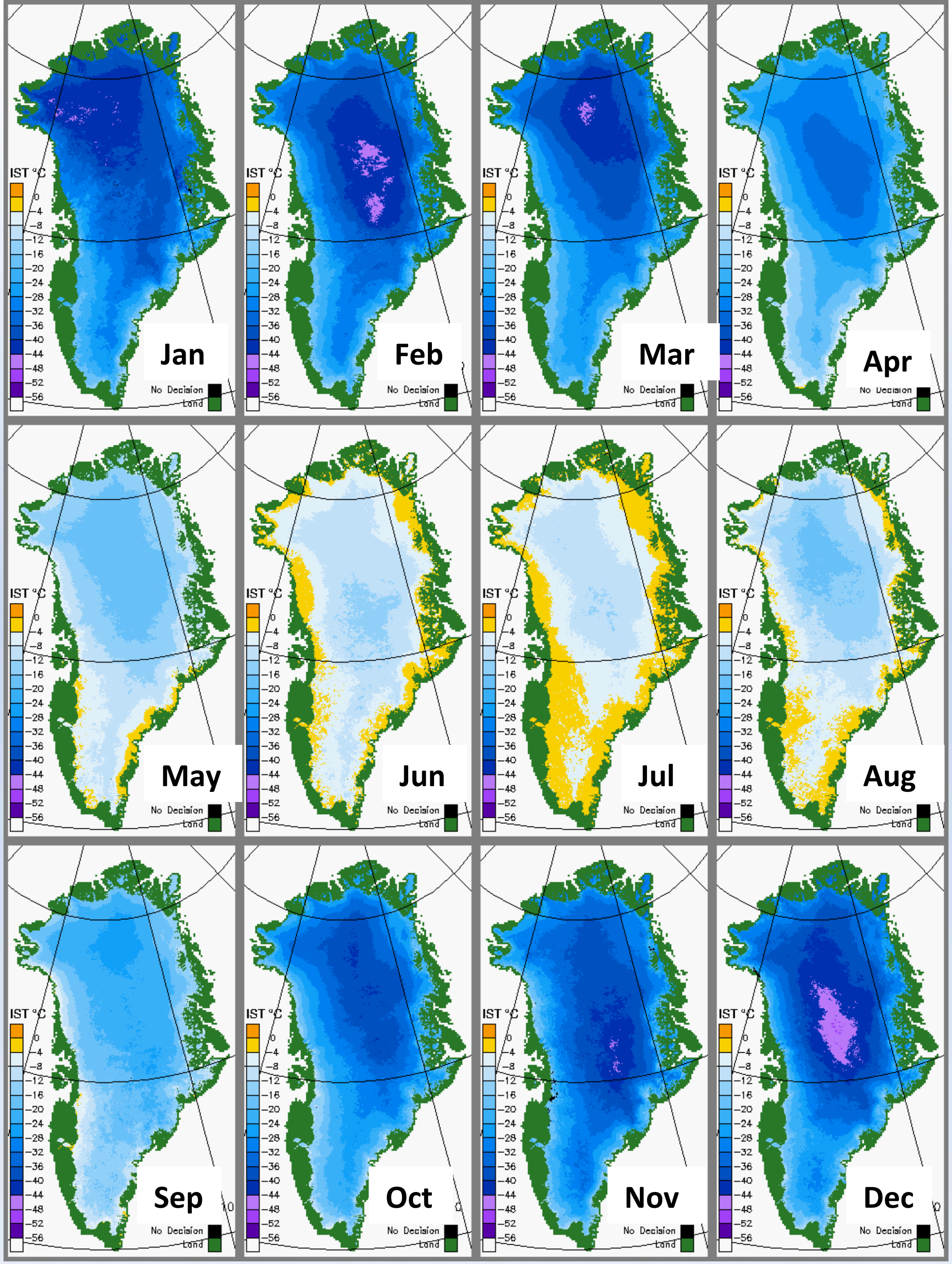
Can compare MODIS IST directly with model-derived ice sheet surface skin temperatures

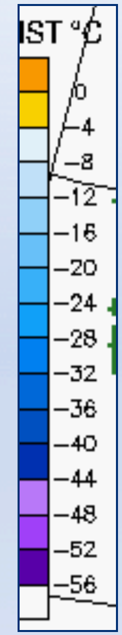


Used MERRA301.prod.assim.tavgM_2d_rad_Nx -- surface skin temperature

Monthly-mean MODIS ice-surface temperature (IST) color-coded maps for 2010

IST cannot be acquired through cloud cover



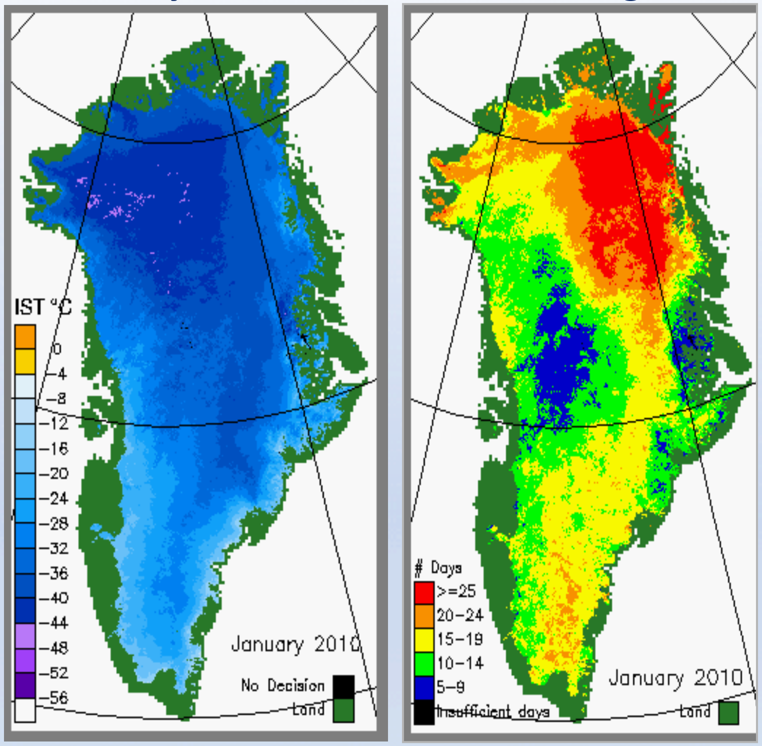


http://modis-snow-ice.gsfc.nasa.gov

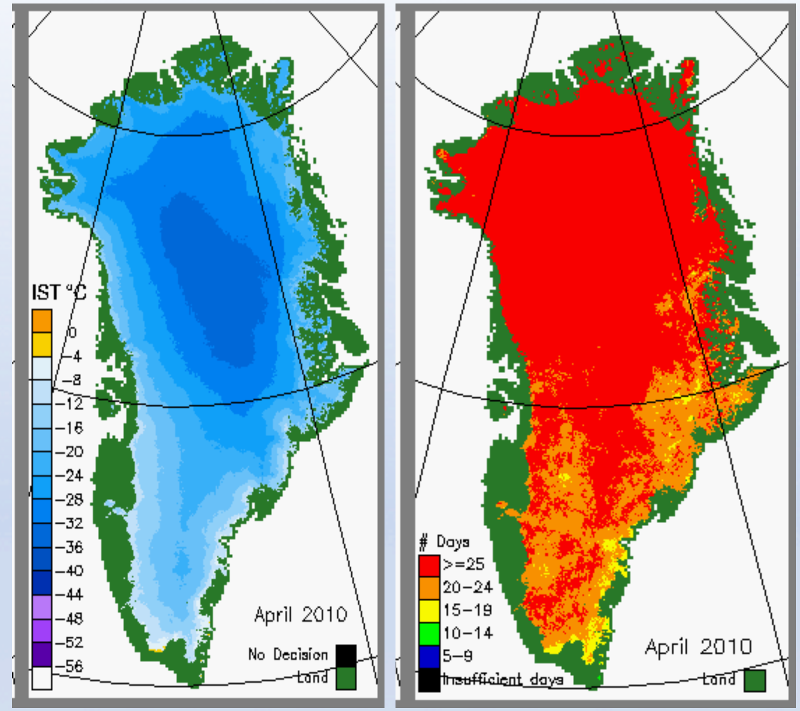
Hall, D.K., J.C. Comiso, N.E. DiGirolamo, C.A. Shuman, J.R. Key and L.S. Koenig, 2012: A Satellite-Derived Climate-Quality Data Record of the Clear-Sky Surface Temperature of the Greenland Ice Sheet, *Journal of Climate.*

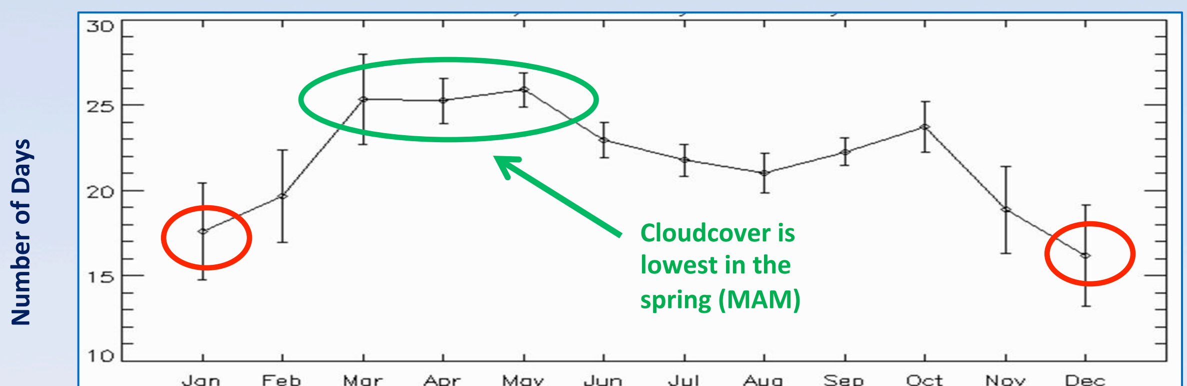
Coverage of Monthly-Mean IST Maps

January 2010 IST **Coverage**



April 2010 IST **Coverage**

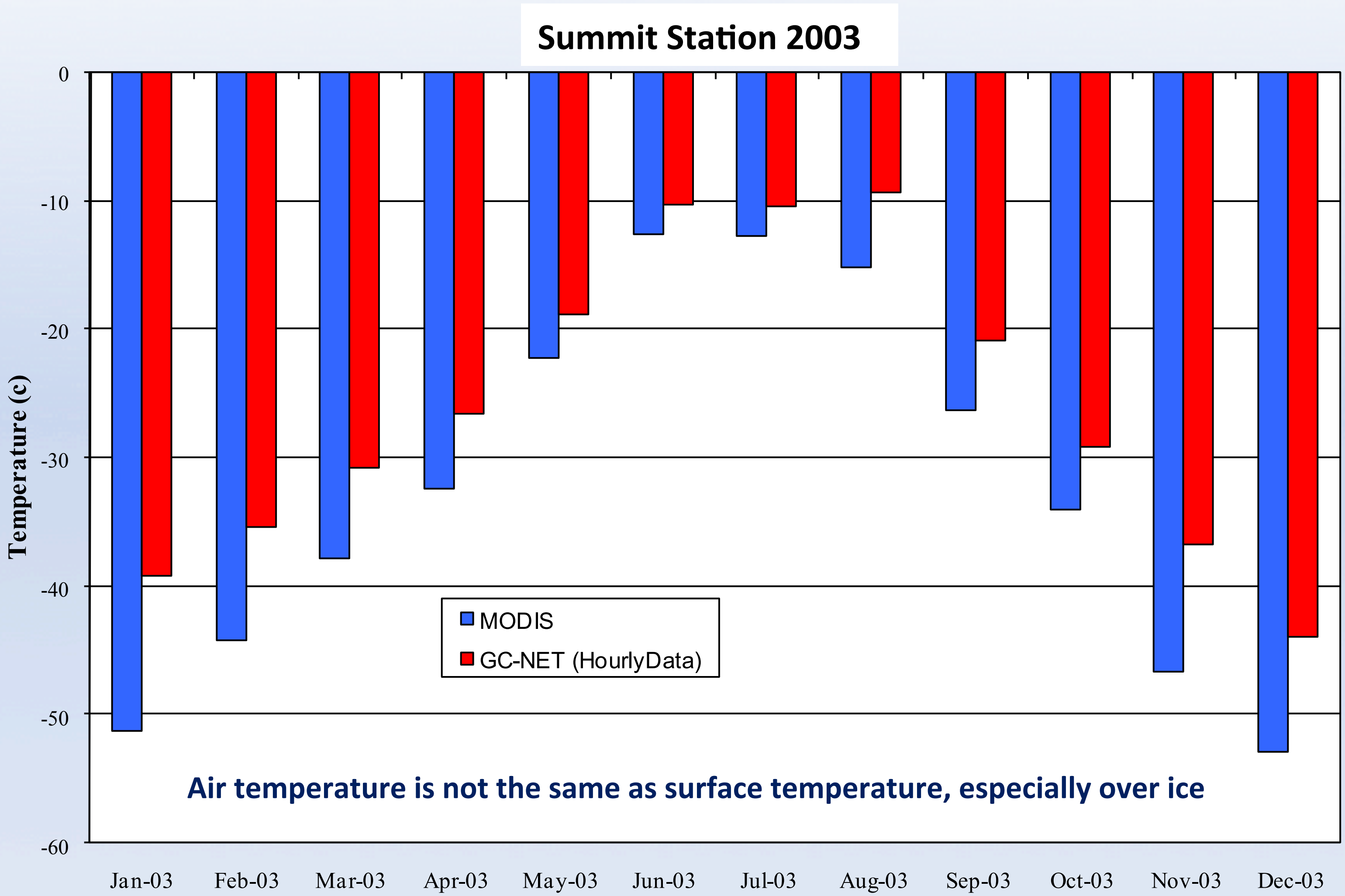




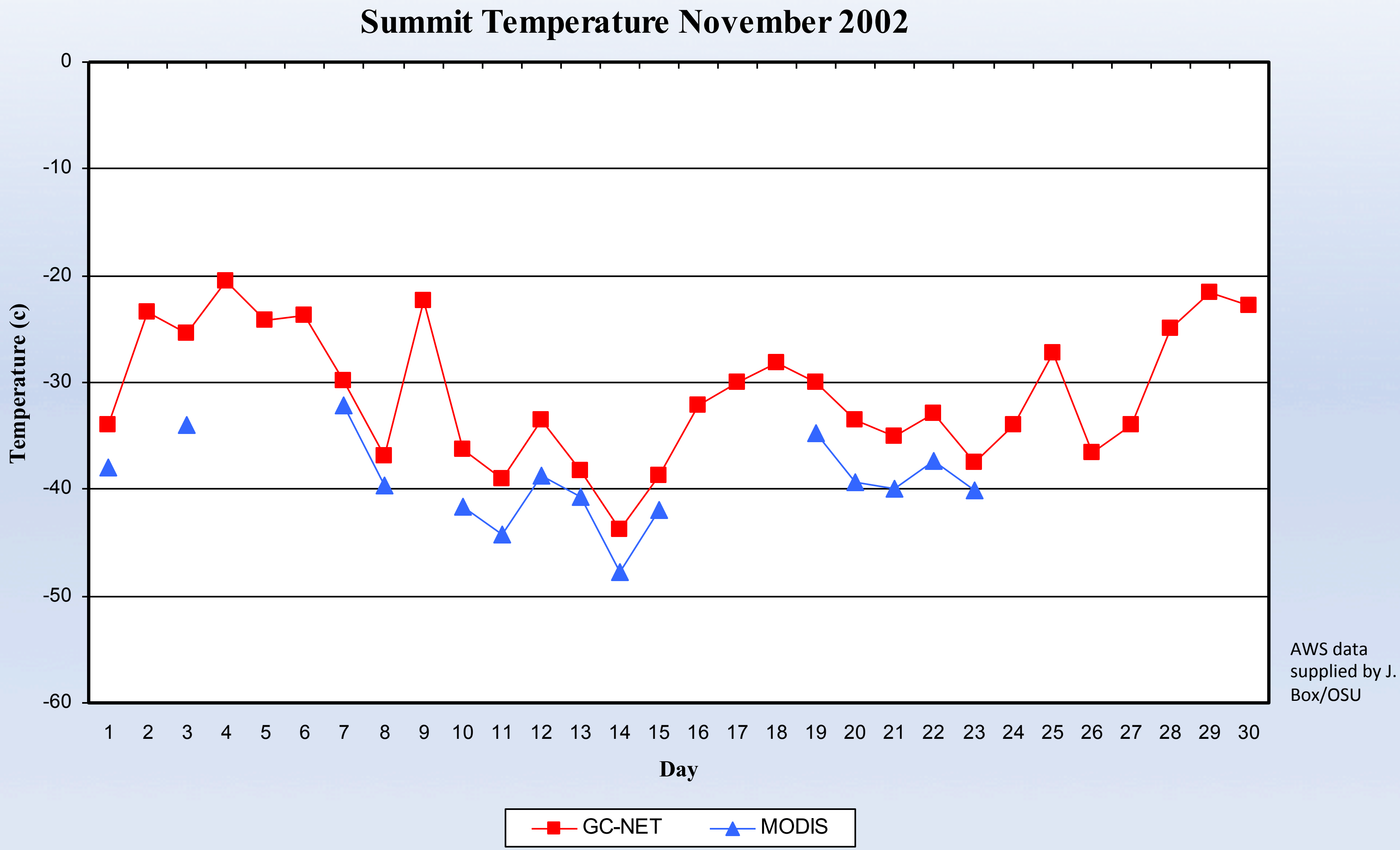
Average number of days (2000 – 2010) available to create the monthly-mean IST maps by month

Hall et al., 2012, *JCLIM*

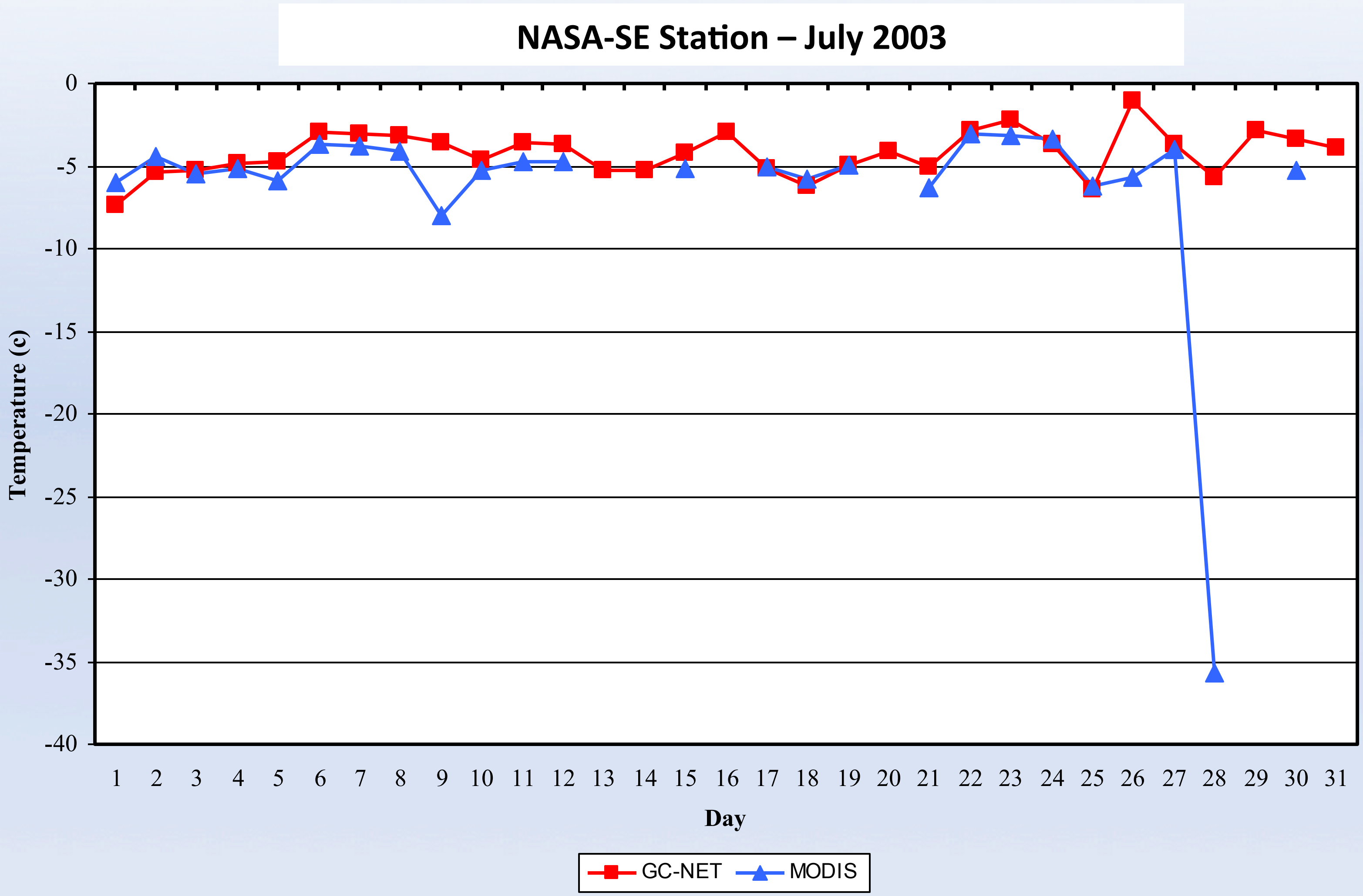
Comparison of MODIS IST and AWS near-surface air temperature



AWS data supplied by J. Box/OSU


Summit Temperature November 2002
Temperature (c)
0
-10
-20
-30
-40
-50
-60
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Day
GC-NET
MODIS
AWS data supplied by J. Box/OSU

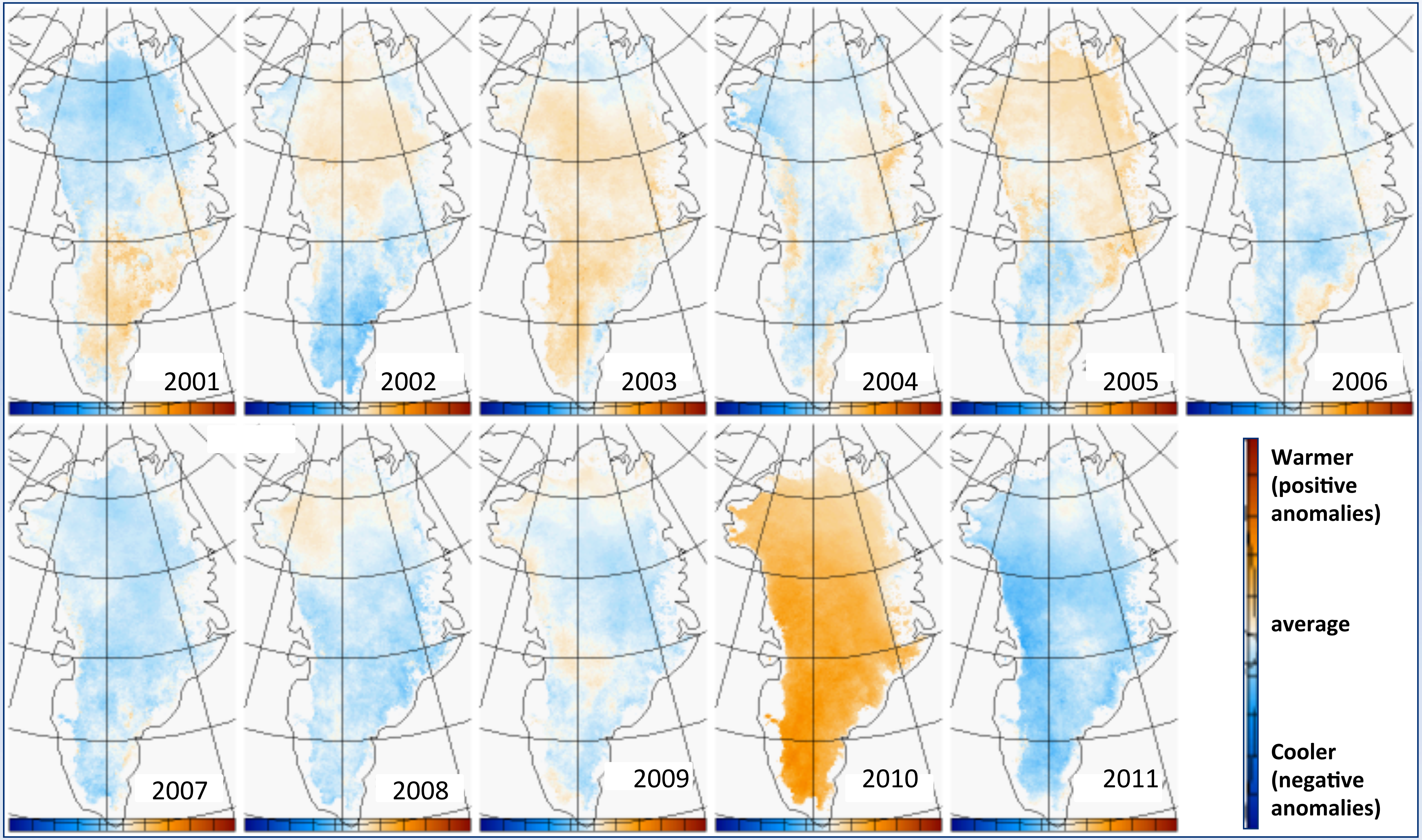
Comparison of MODIS IST and AWS near-surface air temperature

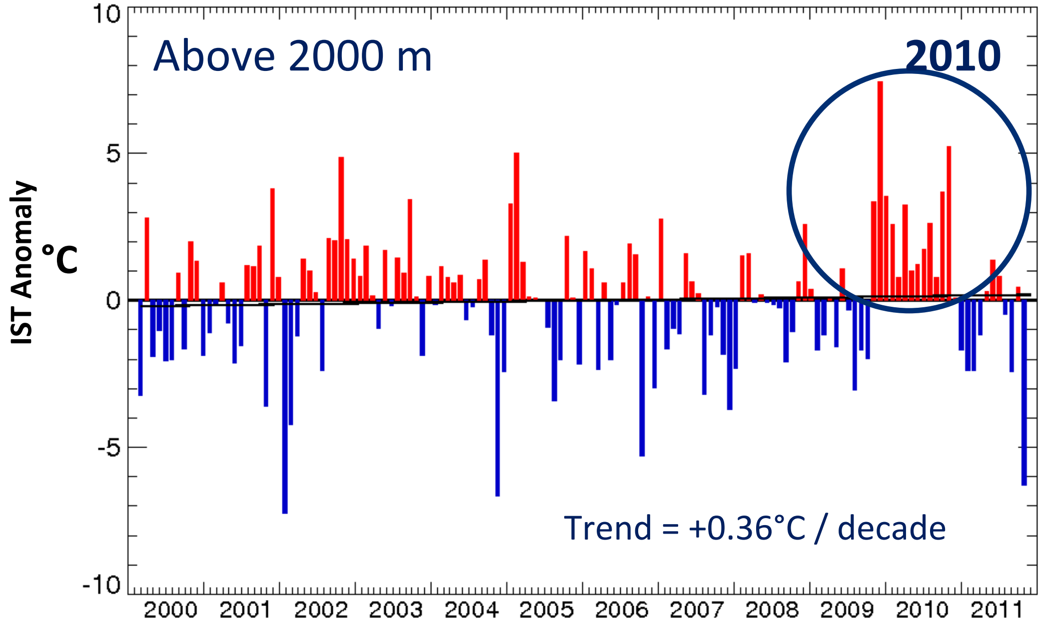


12-Year Trends in Ice Surface Temperature and Melt

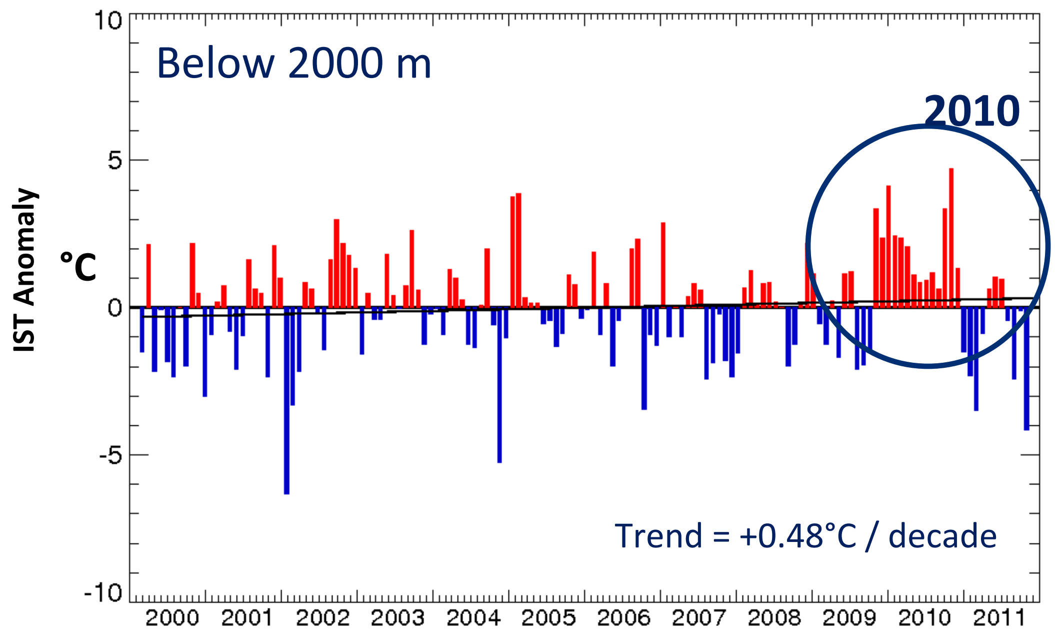
Because the record is short, the trends are not statistically significant and can change with each new data point

Annual MODIS IST Anomalies Based on 11-yr Record





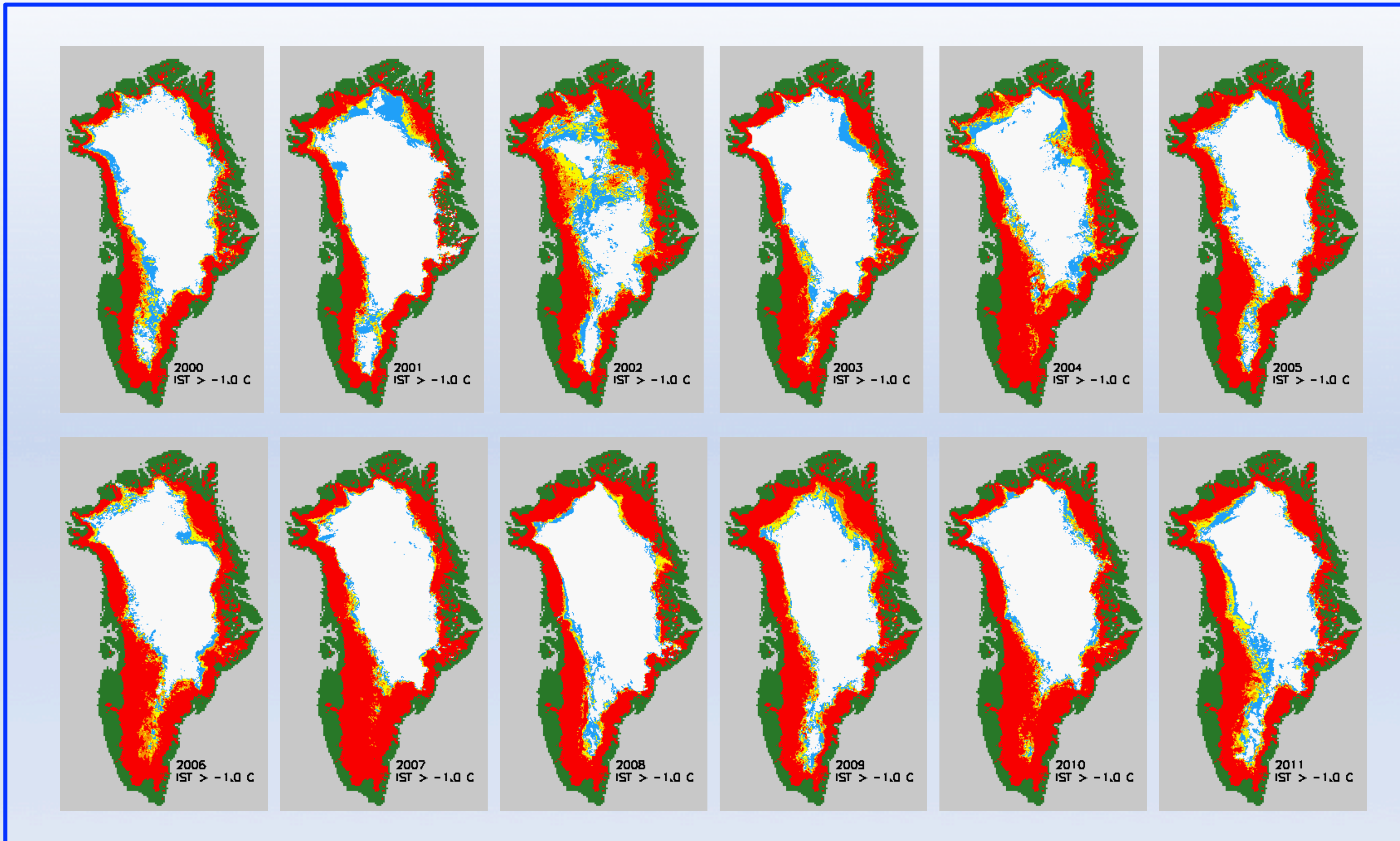
IST Anomalies



Greater IST increase below ~2000 m, consistent with ATM, ICESat and GRACE measurements showing greater mass loss below ~2000 m

Surface melt above ~1500 m is refrozen and retained (Humphrey et al., 2012), while melt below ~1500 m runs off, contributing to SLR

Maximum Melt Extent based on the MODIS IST ESDR, 2000 – 2011



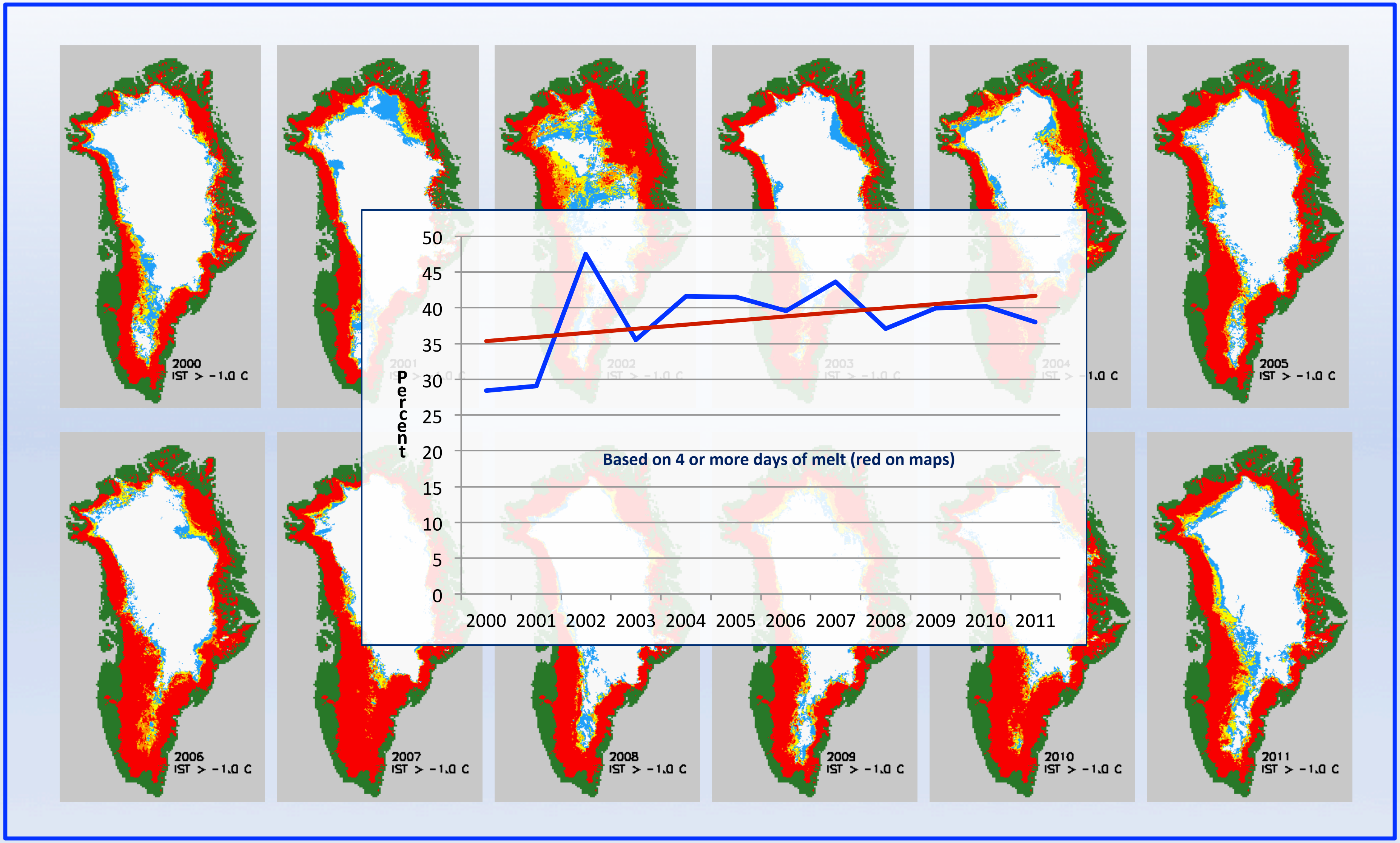
Only 1 day of melt in the year

2 days of melt

3 days of melt in the year

4 or more days of melt

Maximum Melt Extent based on the MODIS IST ESDR, 2000 – 2011



*Based on melt = IST>-1°C

Only 1 day of melt in the year

2 days of melt

3 days of melt in the year

4 or more days of melt

Satellite-Derived Melt Maps

•Passive- and active-MW instruments detect surface and near-surface melt whereas IR instruments detect only surface melt;

•Must resolve issues in measuring melt extent to provide ice sheet modelers with more accurate information.

Estimated potential maximum sea level rise from the total melting of present-day glaciers

Location	Volume (km^3)	Potential sea-level rise (m)
East Antarctic ice sheet	26,039,200	64.80
West Antarctic ice sheet	3,262,000	8.06
Antarctic Peninsula	227,100	.46
Greenland	2,620,000	~7.2
All other ice caps, ice fields, and valley glaciers	180,000	.45
Total	32,328,300	80.32

U.S. Department of the Interior
U.S. Geological Survey

After Williams and Hall, 1993

Conclusions

•Changes in Arctic sea ice, duration of ice cover on lakes, mountain glaciers, snow cover, permafrost and the Greenland Ice Sheet have been observed;

•ATM, ICESat and GRACE measurements show mass loss of the Greenland Ice Sheet below ~2000 m in elevation;

•A consistent pattern of ice sheet warming and increasing melt extent has been observed with different instruments, though the magnitude of changes differs;

•IST can validate skin-temperature output of models, and as input to ice dynamics models, to improve accuracy of ice sheet mass balance and SLR estimates.