The Arctic Land Water Cycle

Input - Output = Storage Change

$$P + G_{in} - (Q + ET + G_{out}) = \Delta S$$

$$R_n - G = L_e + H$$

Observe and predict:

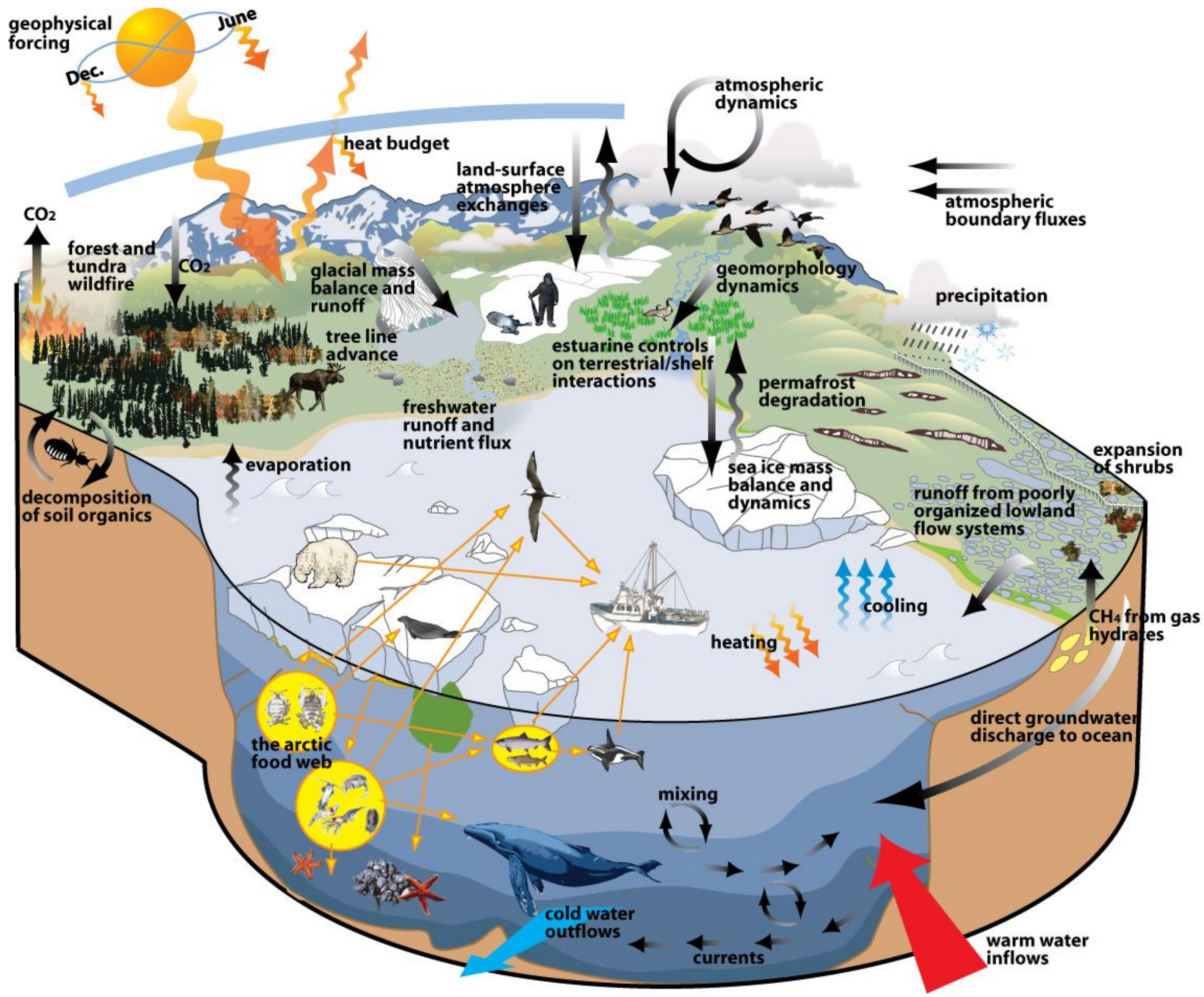
- Precipitation (solid, liquid)
- River runoff (discharge)
- Land Ice
- Snow Cover

Boundary information:

- Temperature & Permafrost
- Salinity
- Vegetation

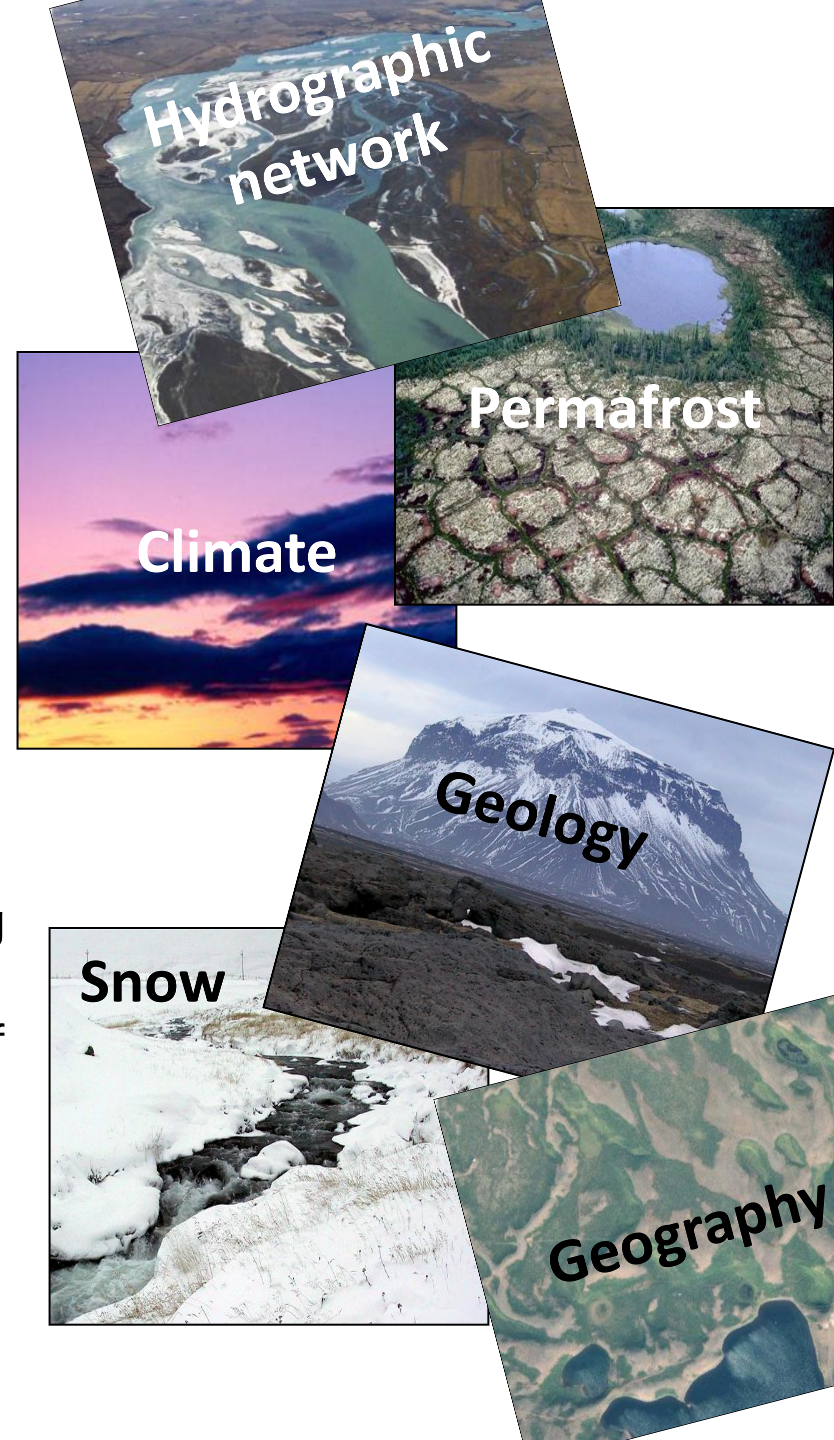
Arctic Water Cycle:

- Moisture flux convergence
- Evolution of the ice mass
- Oceanic transports



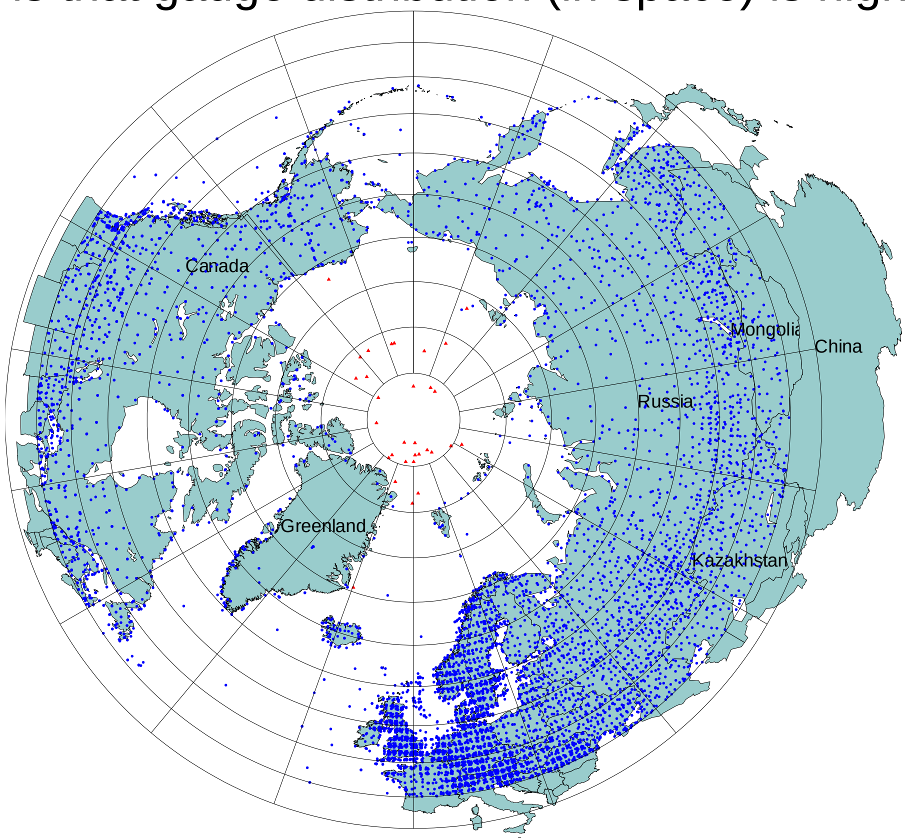
Arctic Land Water Cycle: key features

- •Arctic Ocean drainage is ~2/3 Eurasia, 1/3 N America
- •About 2/3 of freshwater flux from land, balance from ocean P-E
- •Ocean freshwater balance is negative (unlike other oceans)
- •Low net radiation environment => low ET
- •Arctic land would be a desert if at lower latitudes (P ~ 400 mm)
- •P, ET both generally decline S to North
- •Snow redistribution is a key process
- •Summer precipitation is substantial portion of annual total, small contribution to annual runoff, large part of annual ET due to strong seasonal energy (Rnet) variation.
- •Winter precipitation contributes most runoff
- •Much runoff occurs in a short period following spring ice breakup
- •Forested area important fraction of the Arctic drainage area

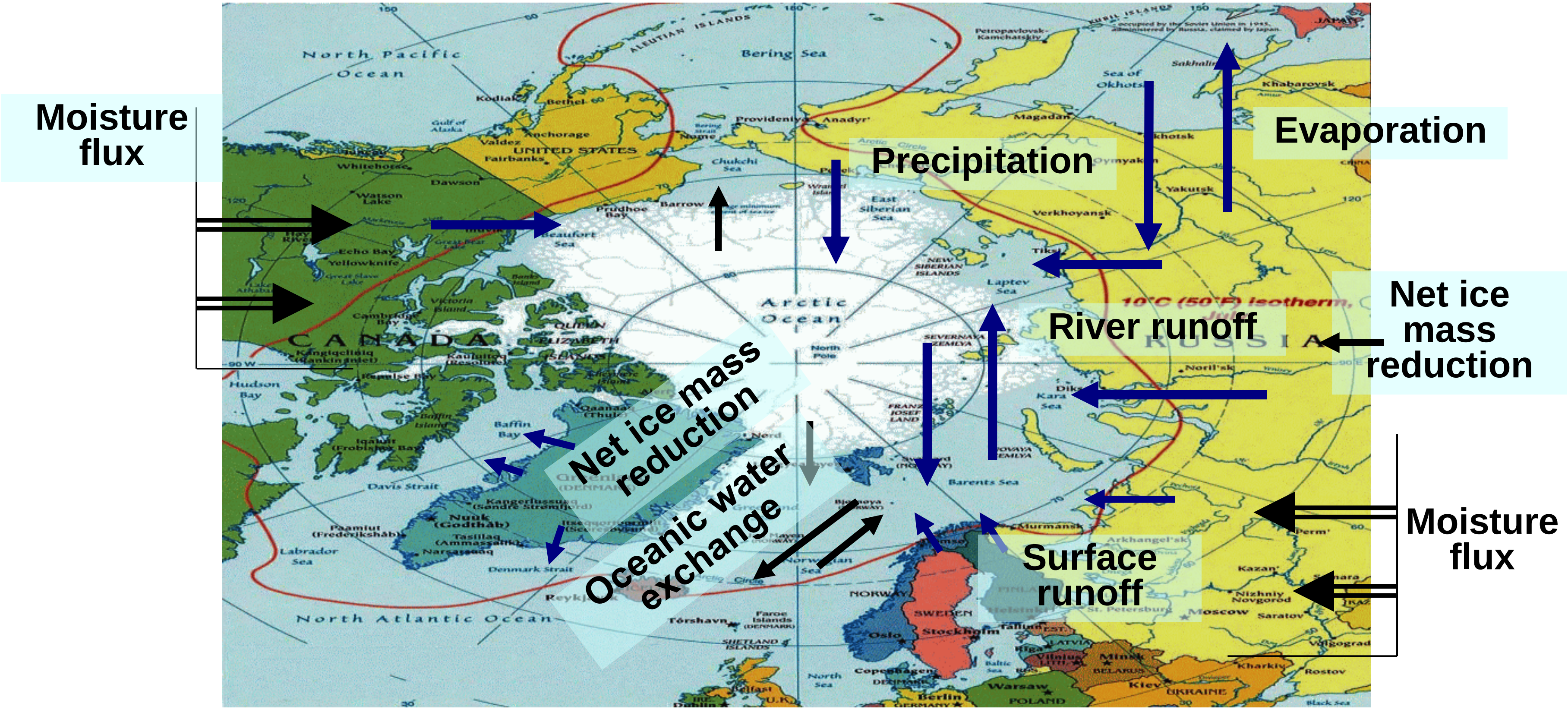


Arctic Land Water Cycle: Measurement difficulties

- Most of the region is remote, access difficult (e.g., expense of running USGS stream gauges in Alaska -- ~ 5-10 x relative to lower 48).
- Station densities (especially precipitation) tend to be where the population is (hence major gaps in Arctic interior)
- Extreme environment, hard on instrumentation
- Solid precipitation measurement extremely difficult due to wind effects on gauges (alternate strategy is to measure accumulated snow on ground)
- Result of which is that gauge distribution (in space) is highly uneven

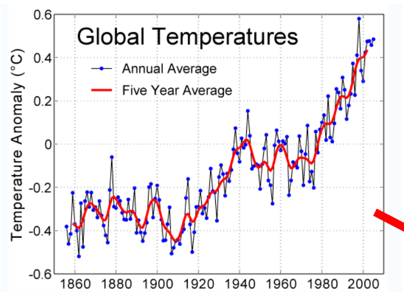


The Arctic Hydrological Cycle



not a closed system but has impact from horizontal atmospheric and oceanic water mass exchange

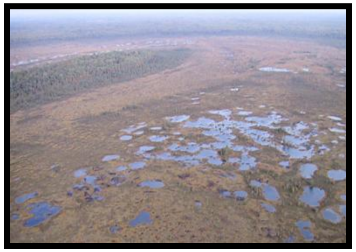
Climate Change and an “Accelerated” Water Cycle ?



Atmospheric Moisture ↑

Evaporation ↑

Snow & Rain ↑



Soil & Surface Wetting ↑

Runoff ↑

Changes in Arctic hydrology:

- Small rises in temperature result in increased melting of snow and ice
- Shift to a rainfall runoff regime, with less seasonal variation in runoff.
- More water ponding; but peatlands dry out due to increased ET.
- Thawing of permafrost will improve infiltration.
- Reduction in ice-jam flooding will impacts on riverbank ecosystems and aquatic ecology.
- Changes in Arctic runoff will affect sea-ice production, deepwater formation in the North Atlantic.

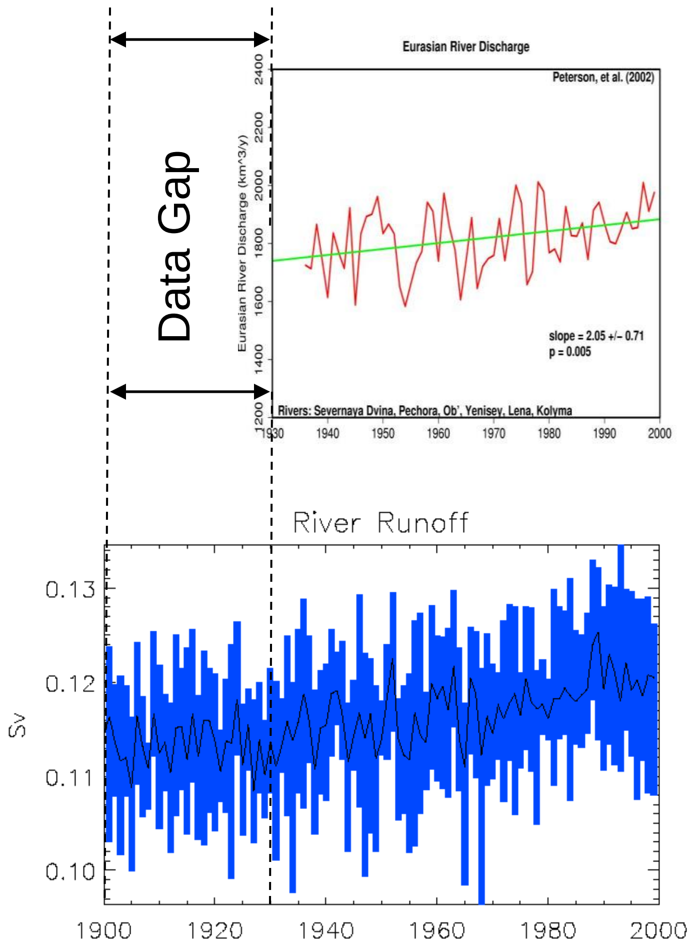
•Changes in Arctic biota:

- Warming should increase biological production
- Changes in species compositions on land and in the sea
- Tendency for poleward shifts in species assemblages and loss of some polar species.
- Changes in sea ice will alter the seasonal distributions, geographic ranges, patterns of migration, nutritional status, reproductive success, and ultimately the abundance and balance of species.
- Biological production in lakes and ponds will increase

•Impacts on human communities:

- Disruptive for communities of indigenous peoples following traditional lifestyles.
- Increased economic costs are expected to affect infrastructure, in response to thawing of permafrost and reduced transportation capabilities across frozen ground and water.
- new opportunities for trade and shipping across the Arctic Ocean
- lower operational costs for the oil and gas industry
- lower heating costs
- Easier access for ship-based tourism

Comprehensive picture also emerging from Earth System Models



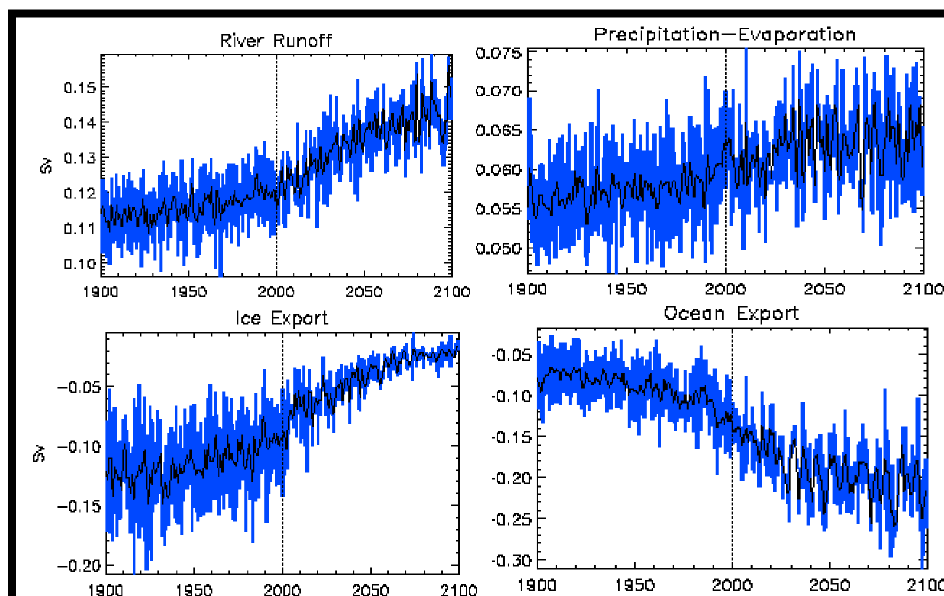
CCSM3 Modeled Eurasian River trend over 20th century = 6.7e-3 Sv/century (2.11 km^3/yr)

Results in 7% increase in Eurasian river flow over the century

Agrees well with observed trends discussed by Peterson et al. (2002) (12%⇑, 2.05 km^3/yr)

Model Forecasts to 2100

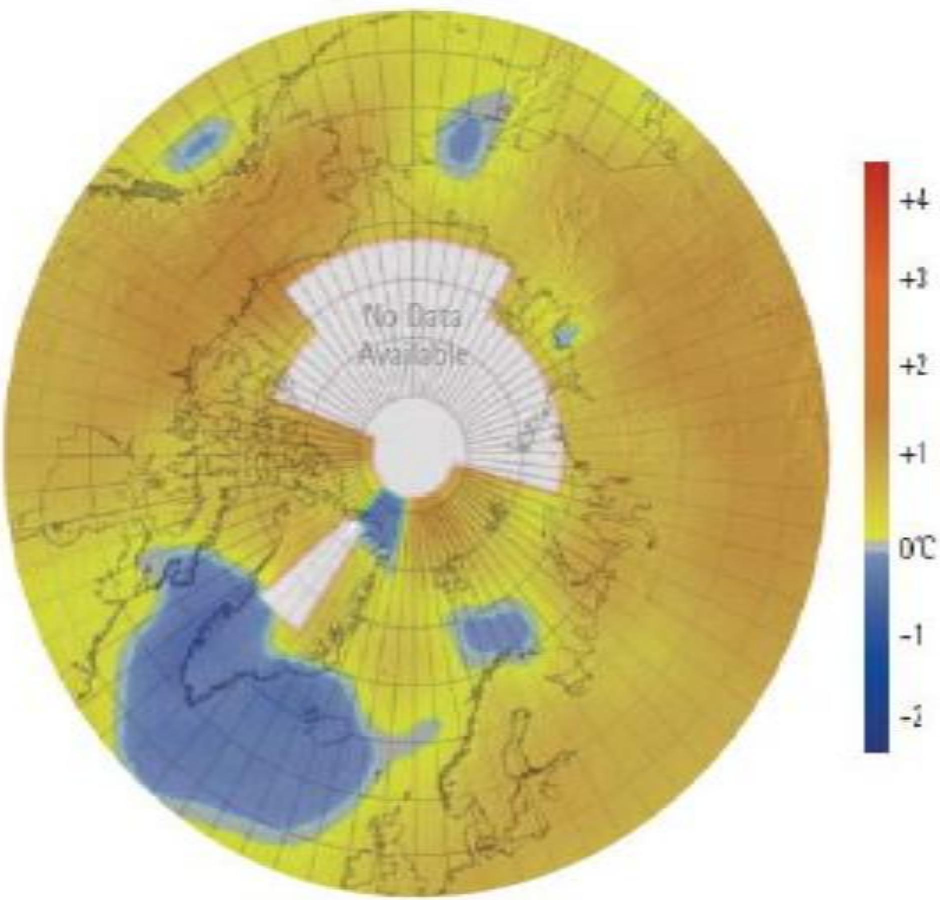
Coherent Tracking of Fresh Water



Holland et al., 2006

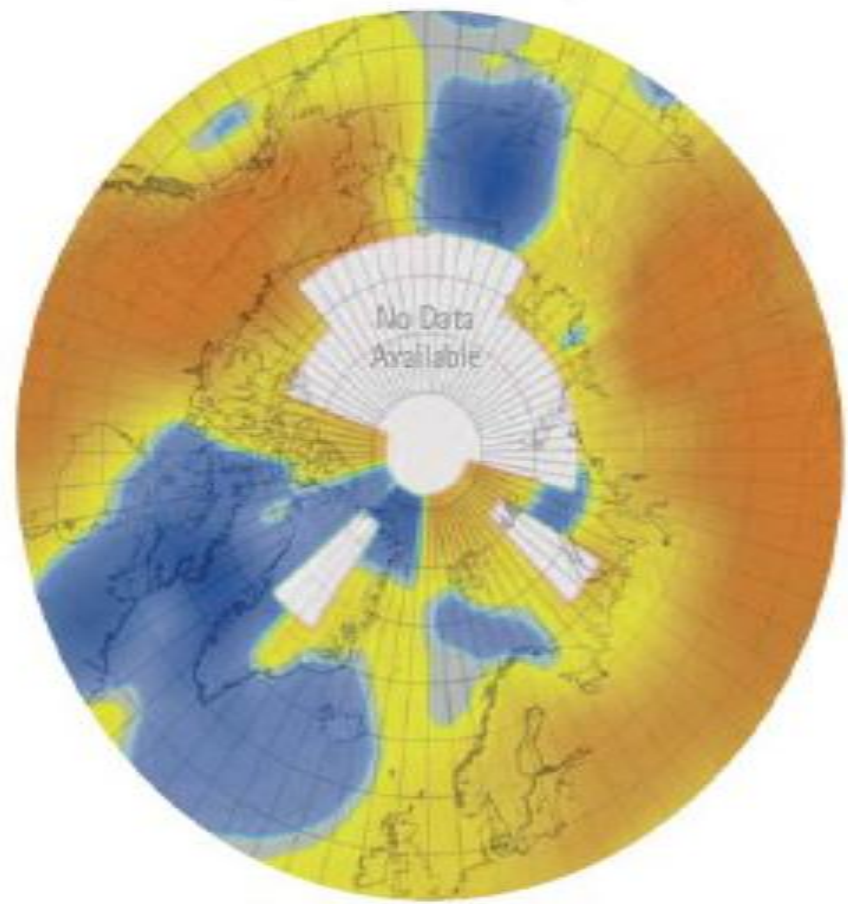
TEMPERATURE

Observed Surface Air Temperature Changes: 1954–2003
(ANNUAL, °C)



The colors indicate the change in temperature from 1954 to 2003. The map indicates annual average temperature change, which ranges from a 2-3°C warming in Alaska and Siberia to a cooling of up to 1°C in southern Greenland.

Observed Surface Air Temperature Changes: 1954–2003
(WINTER: Dec–Feb in °C)

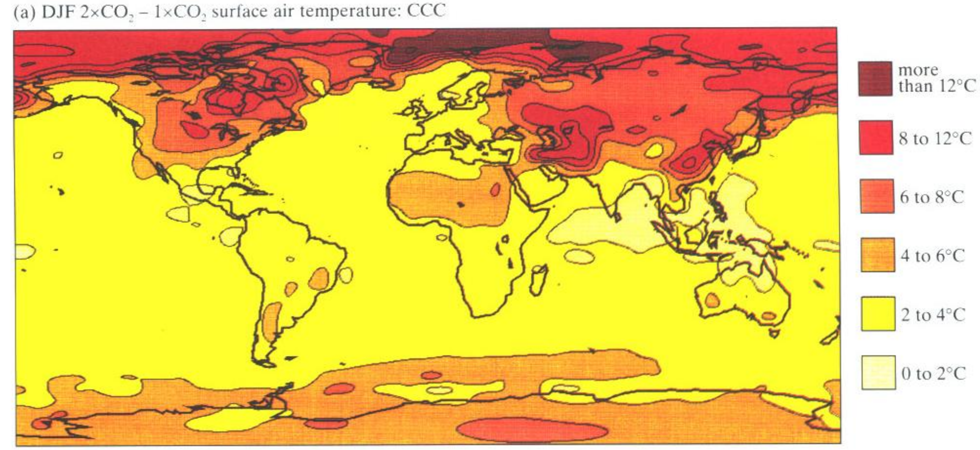


This map indicates the temperature change during the winter months, ranging from a warming of up to 4°C in Siberia and Northwest Canada to a cooling of 1°C over southern Greenland.

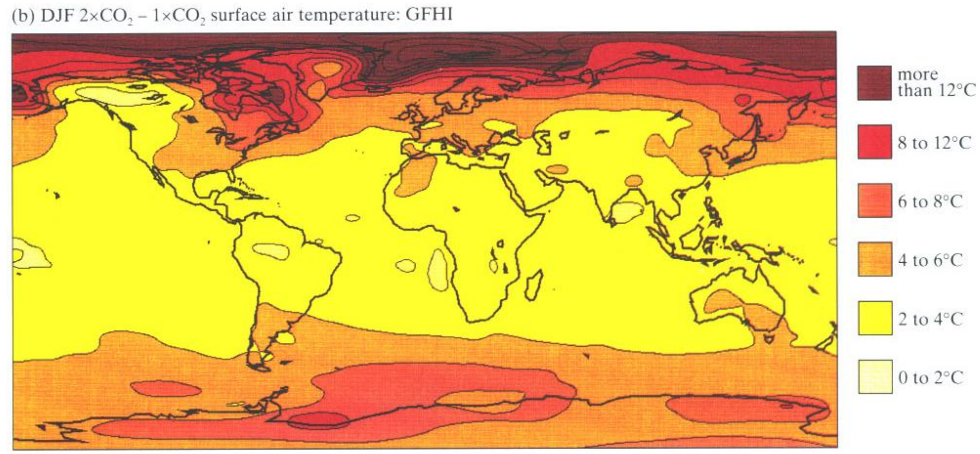
2xCO2 winter (DJF) temperature change from three early climate models (IPCC, 1990).

High-latitude amplification is attributed to positive feedbacks involving sea-ice albedo over ocean and snow albedo over land.

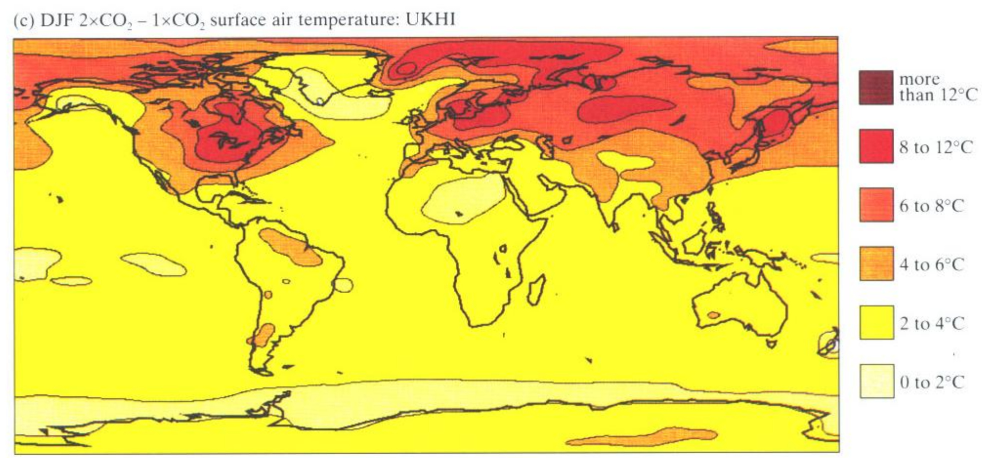
CCCma



GFDL



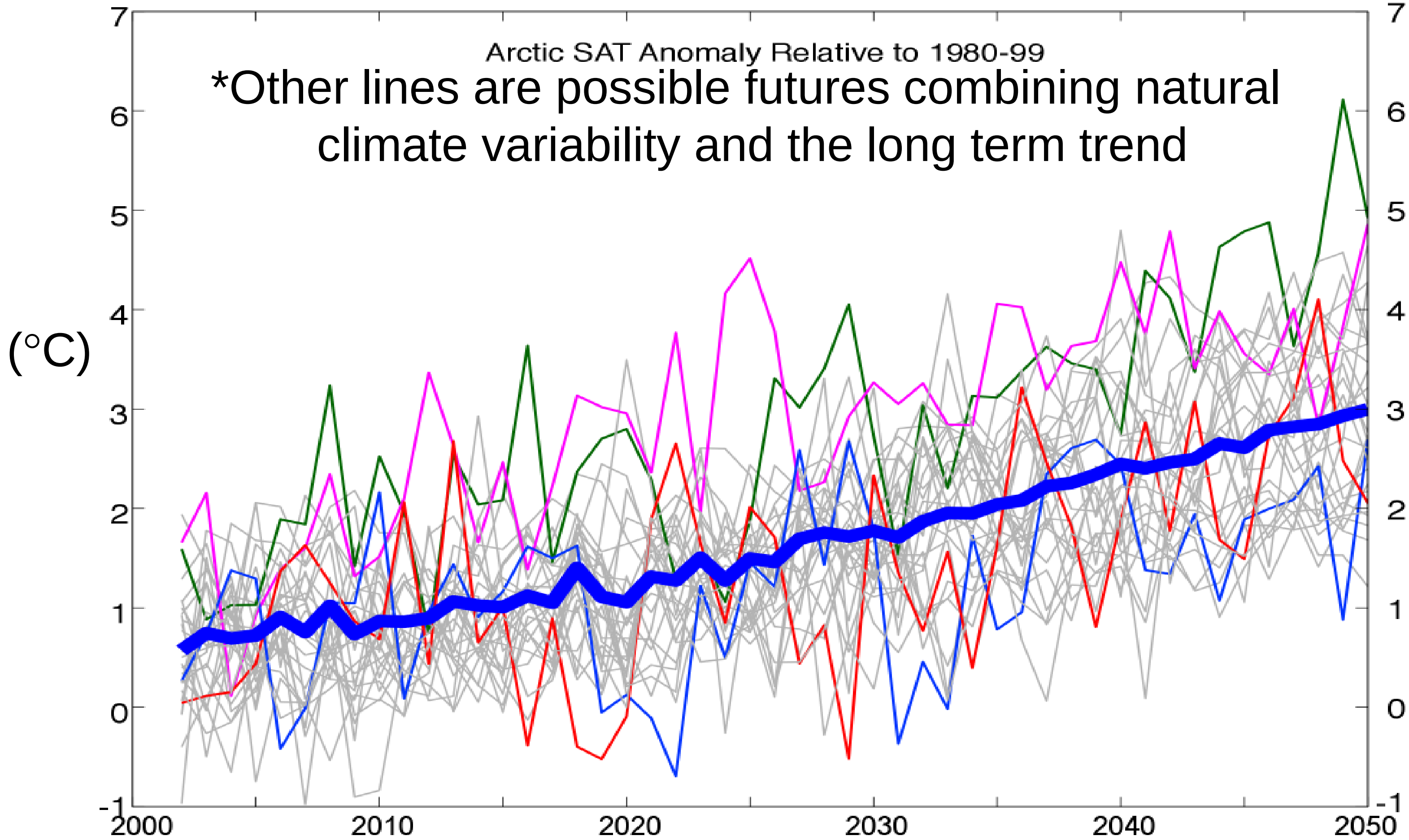
UKMO



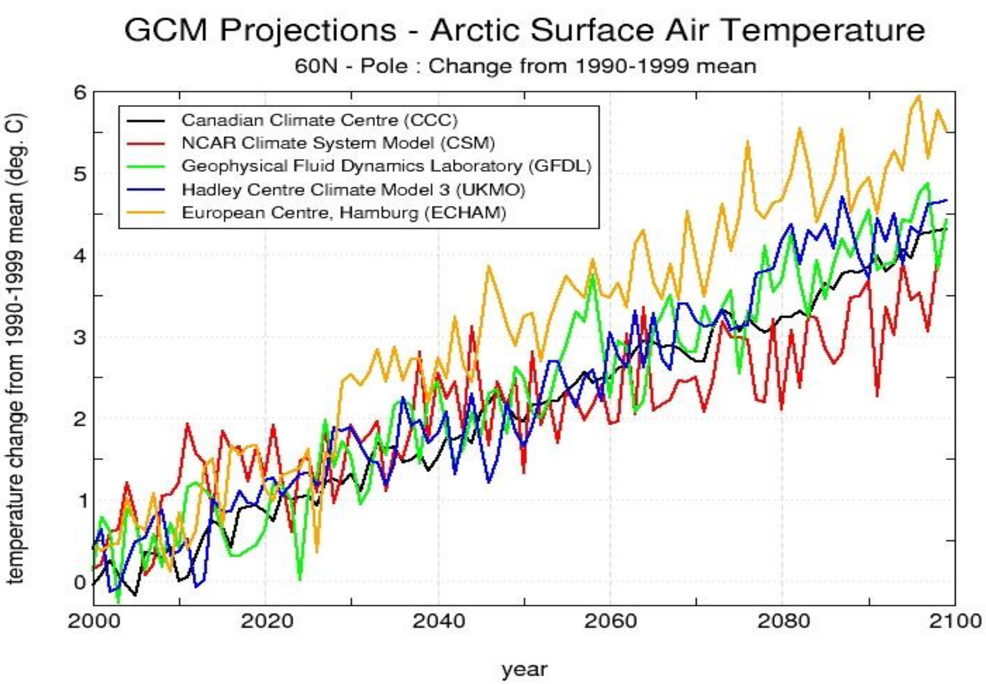
Arctic land temperature forecasts from 12 Models

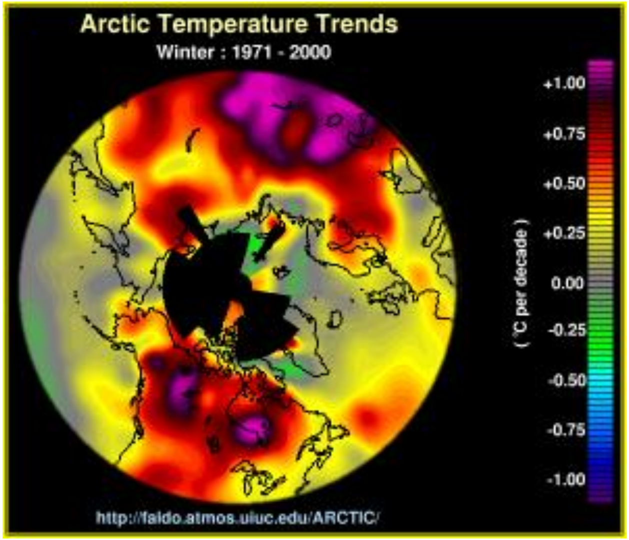
Made available prior to the IPCC Fourth Assessment Report

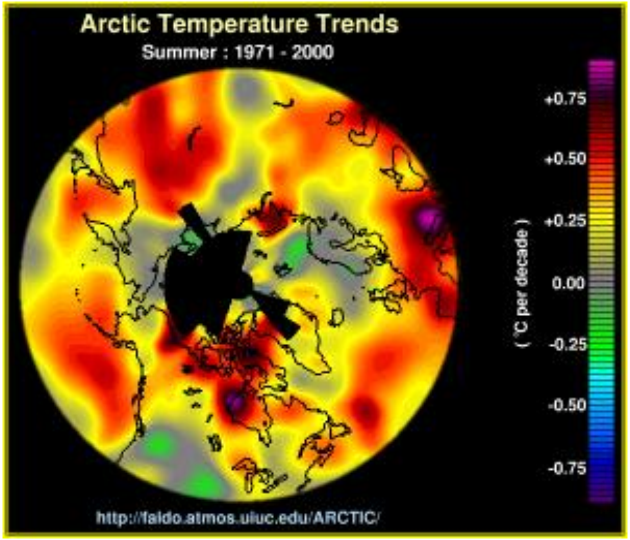
*Thick blue line is average of all forecasts and shows the anthropogenic contribution for a medium emissions scenario with a 3 °C increase by 2050



Our best climate models project that the Arctic will become *warmer. And the Arctic is indeed warming*

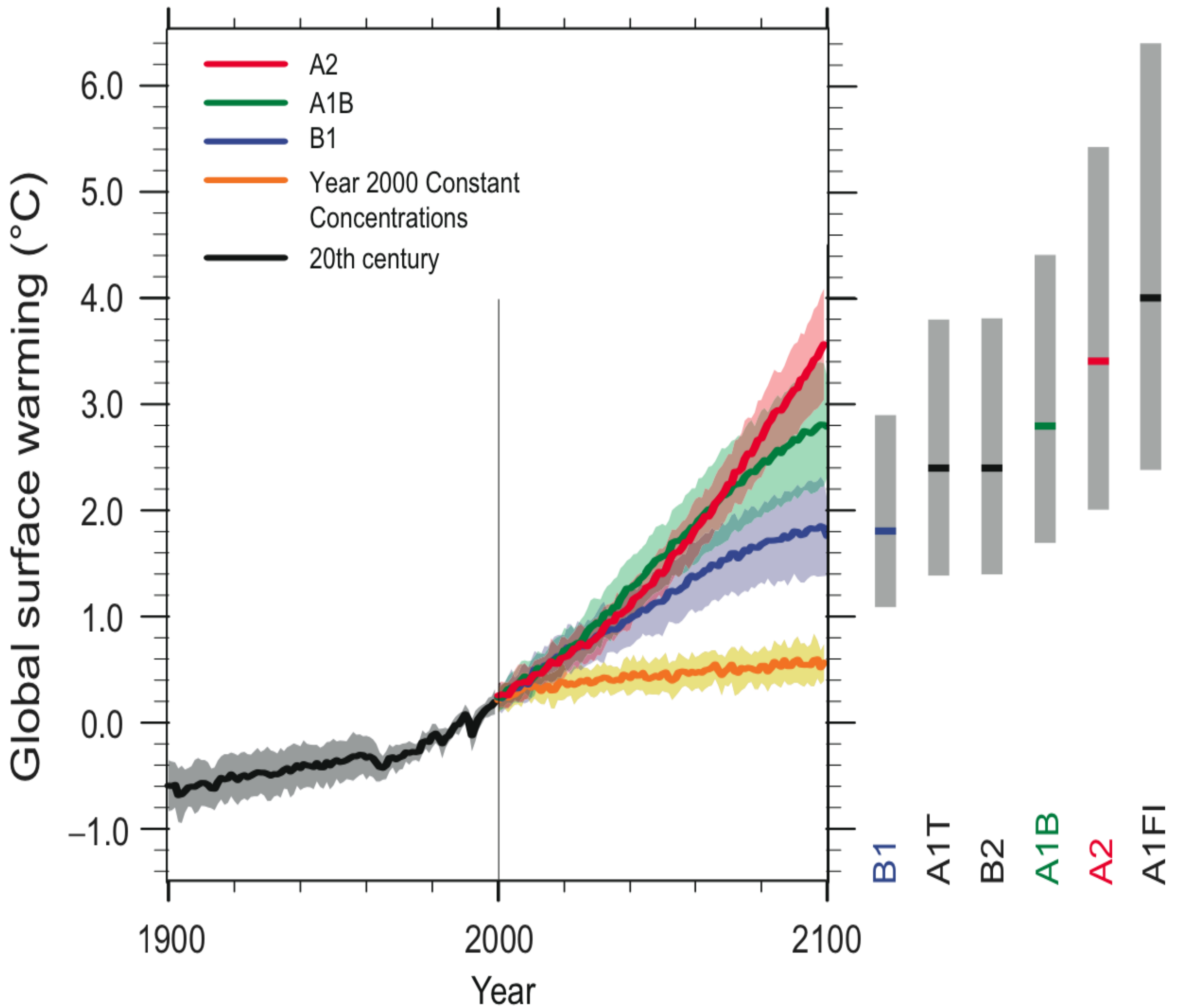






http://zubov.atmos.uiuc.edu/ACIA/
http://zubov.atmos.uiuc.edu/ARCTIC/

Temperature Measurements



- "Warming of the climate system is UNEQUIVOCAL" (IPCC 2007)
- Top 11 warmest years on record have all occurred in the last 12 years. (IPCC 2007)
- 2006 warmest year on record in continental US. (NOAA 1/07)

Alaska is Ground Zero

In past 50 years,

Alaska:
Temperatures have increased

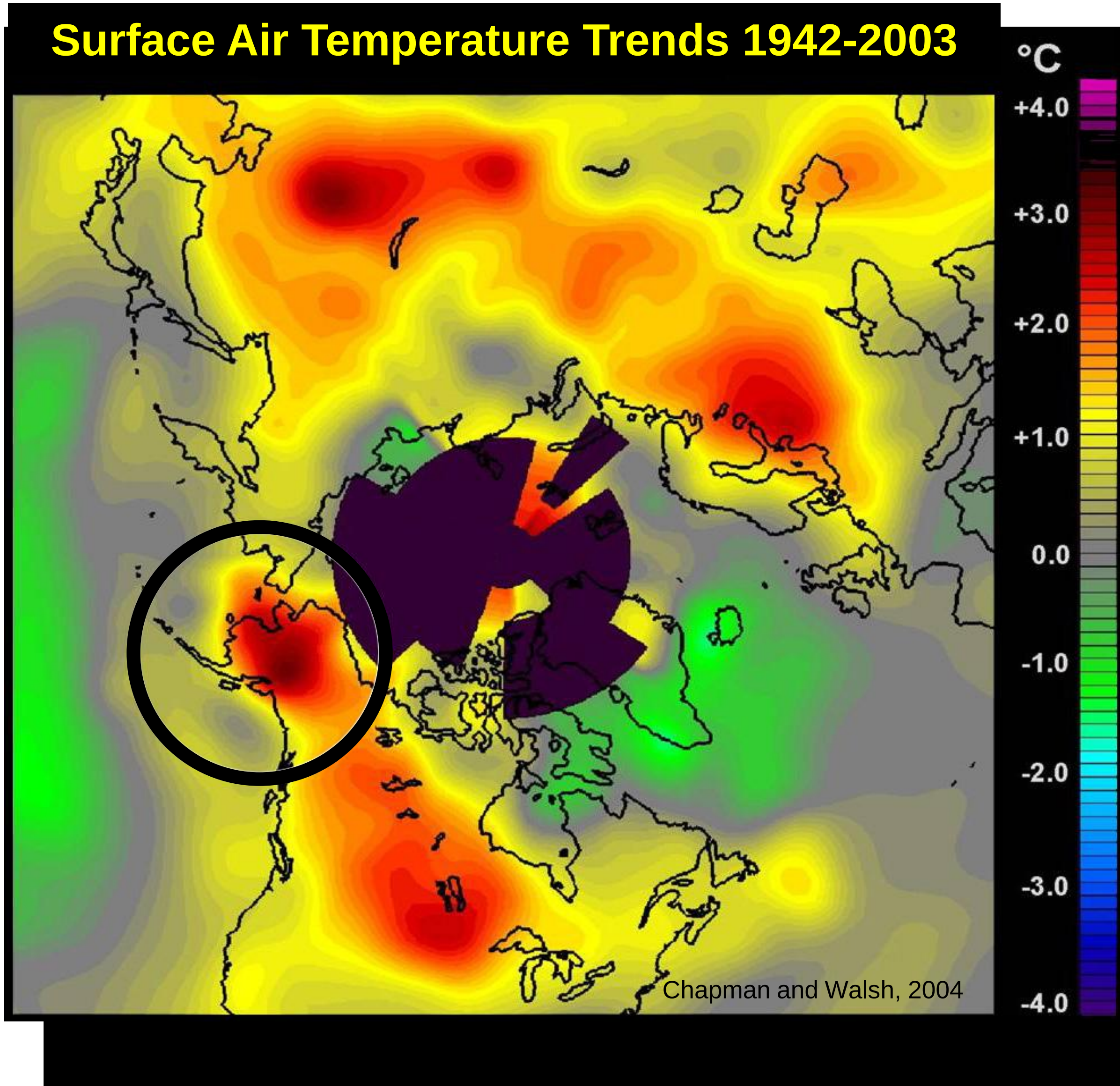
- 4°F overall

(National Assessment Synthesis Team)

Worldwide:
Temperatures have increased

- Slightly more than 1°F

(IPCC 2007)

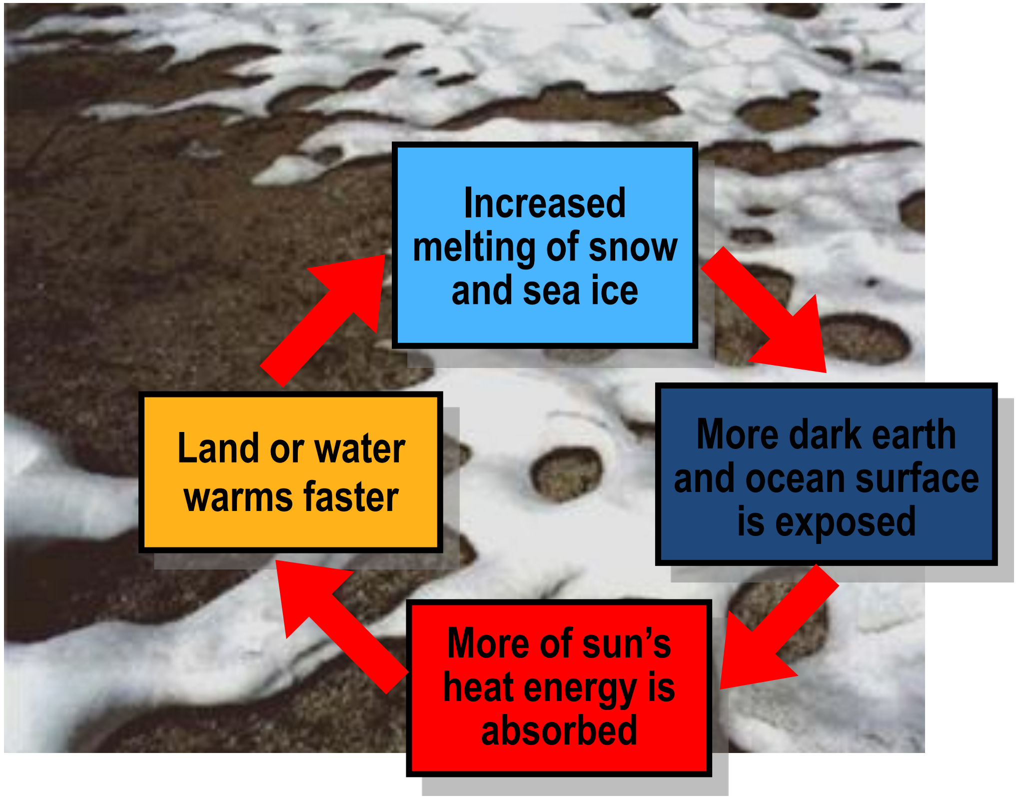


Why has Alaska warmed the most?

The Albedo Effect

- Snow and sea ice reflect 85-90% of sun's energy.
- Ocean surface and dark soil reflect only 10-20%.

(ACIA 2004)

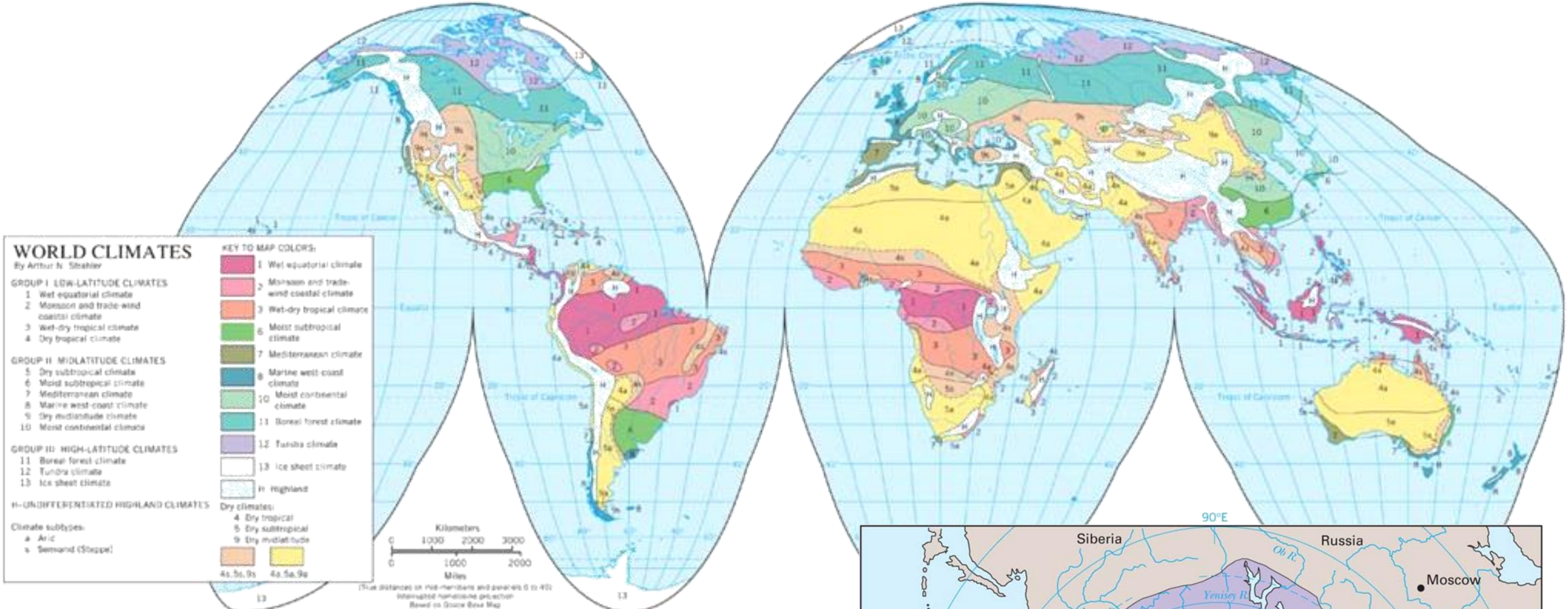


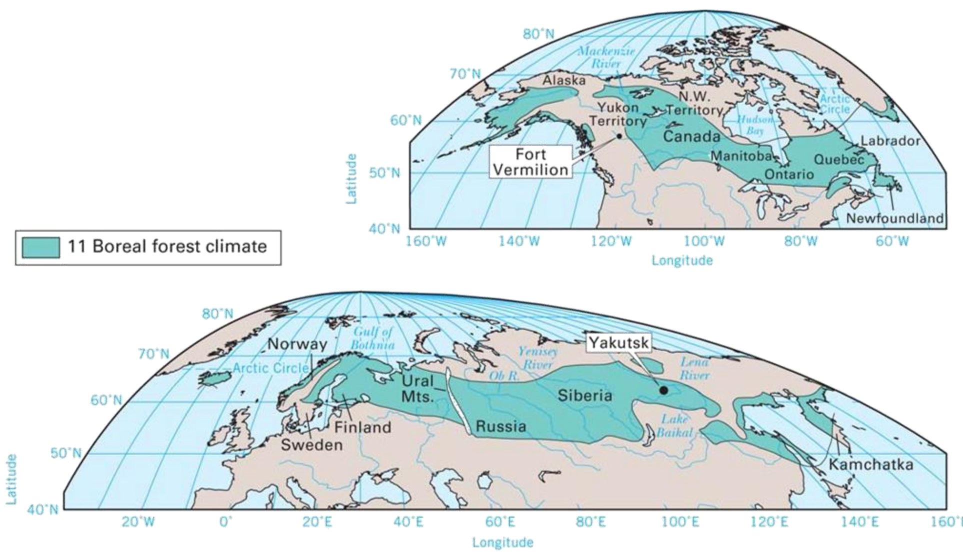
"White shirt versus Black shirt"

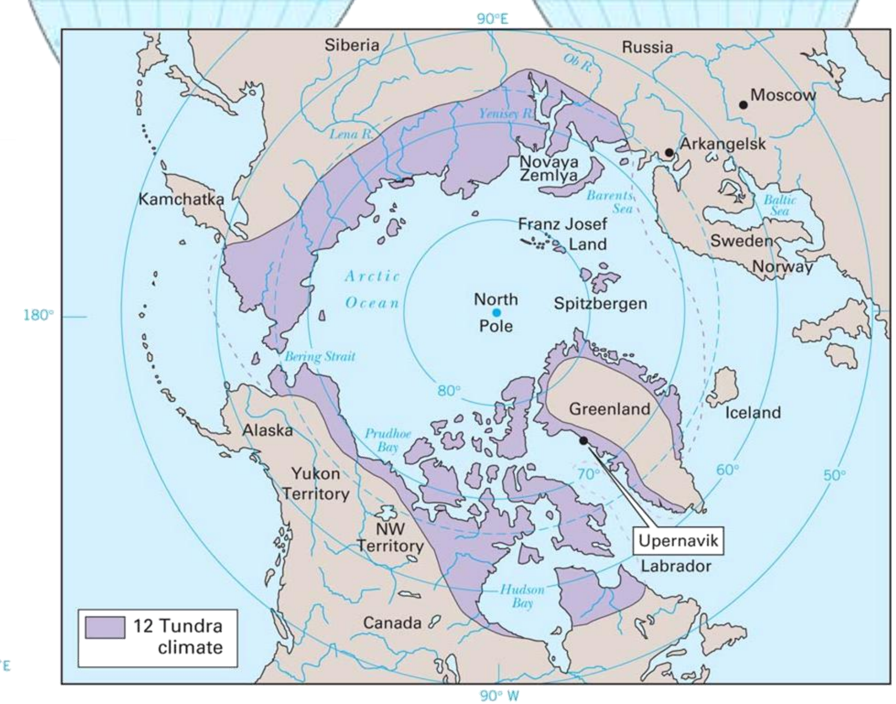
VEGETATION

Three high-latitude Vegetation/Climates:

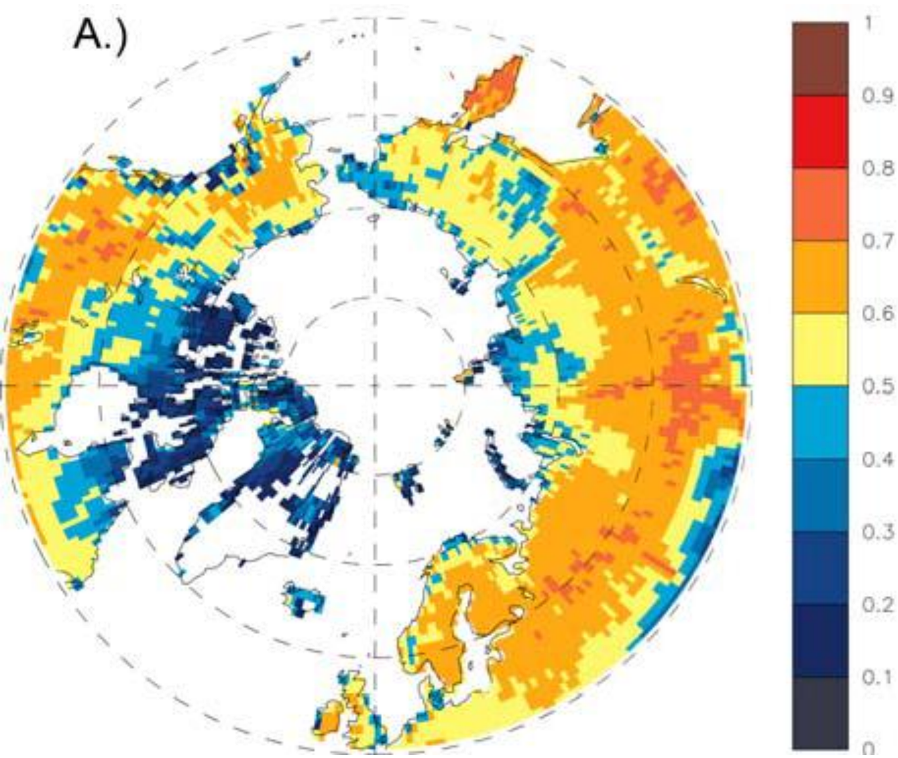
Boreal Forest **Tundra** **Ice Sheet/Glacier**



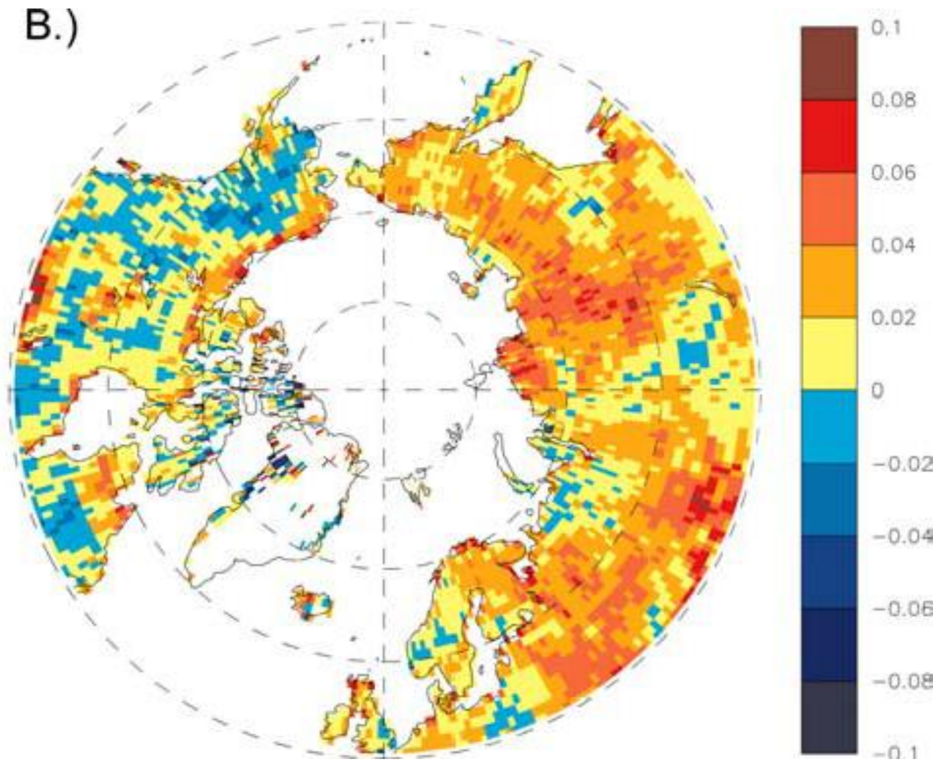




NDVI 20-year Mean



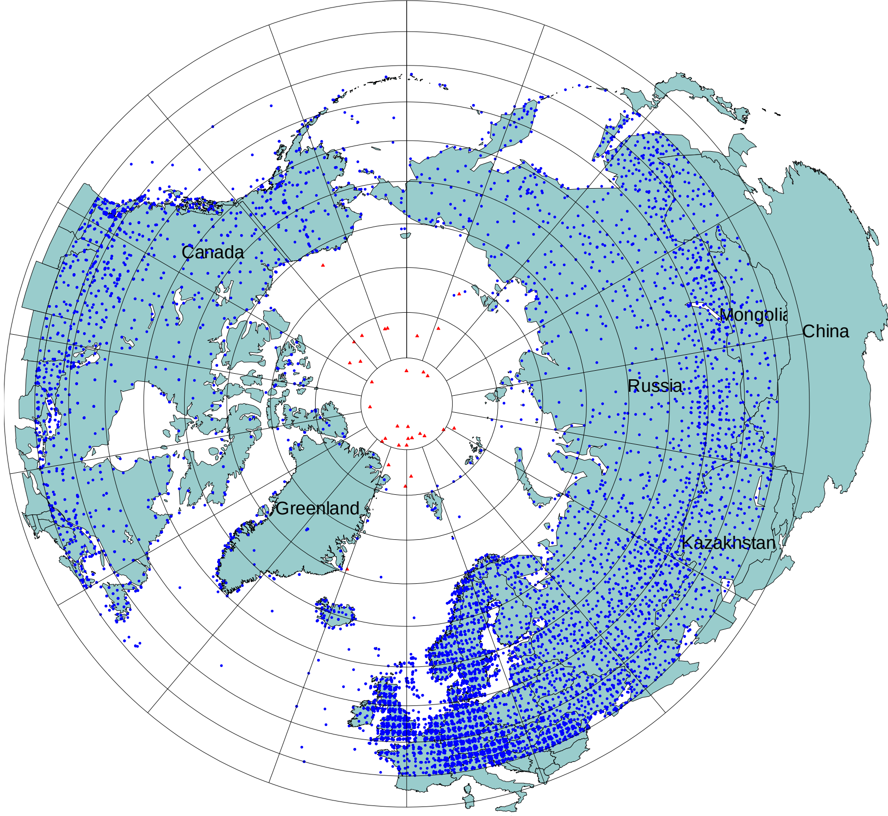
NDVI Change from 1980s to 1990s



Wang and Overland (2003)

PRECIPITATION

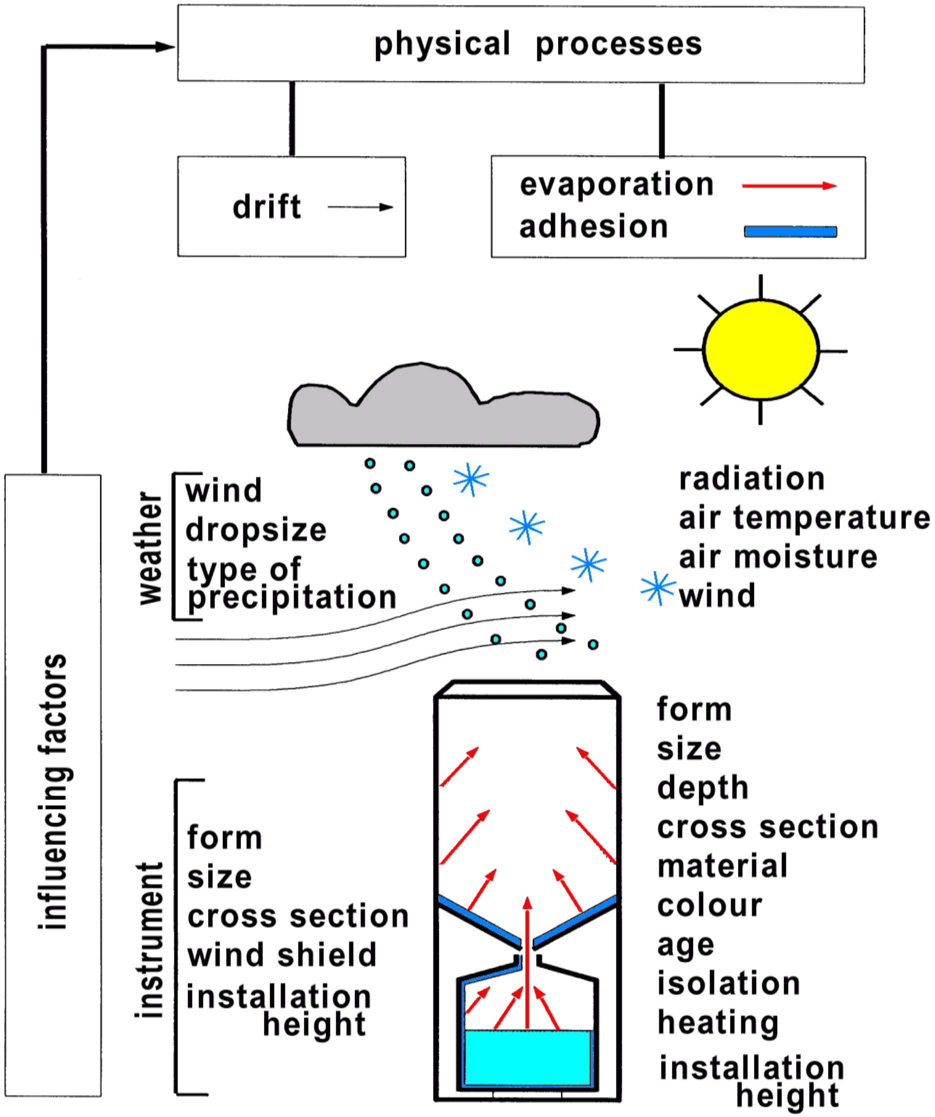
•"It is very likely that precipitation has increased by 0.5% to 1% per decade in the 20th century over most mid- and high latitudes of the Northern Hemisphere continents"(IPCC 2001b)



•Some areas show as much as a 20% increase in annual precipitation over the last 40 years. Areas receiving greatest increases include Alaska, Canada north of 55* N, and the Russian Permafrost-free zone (ACIA 2004).

•Rainfall on snow causes increased rate of snowmelt, which during heavy rain can lead to flashfloods (ACIA 2004).

Systematic gauge measuring error



Precipitation measured by gauges is systematically underestimated because of evaporation, wetting losses and drift of snow and drops by wind across the gauge funnel.

In order to get reliable global or regional precipitation amounts, an adequate correction of the data used or of the product is required.

(Fig. after SEVRUK 1989)

Systematic gauge measuring error

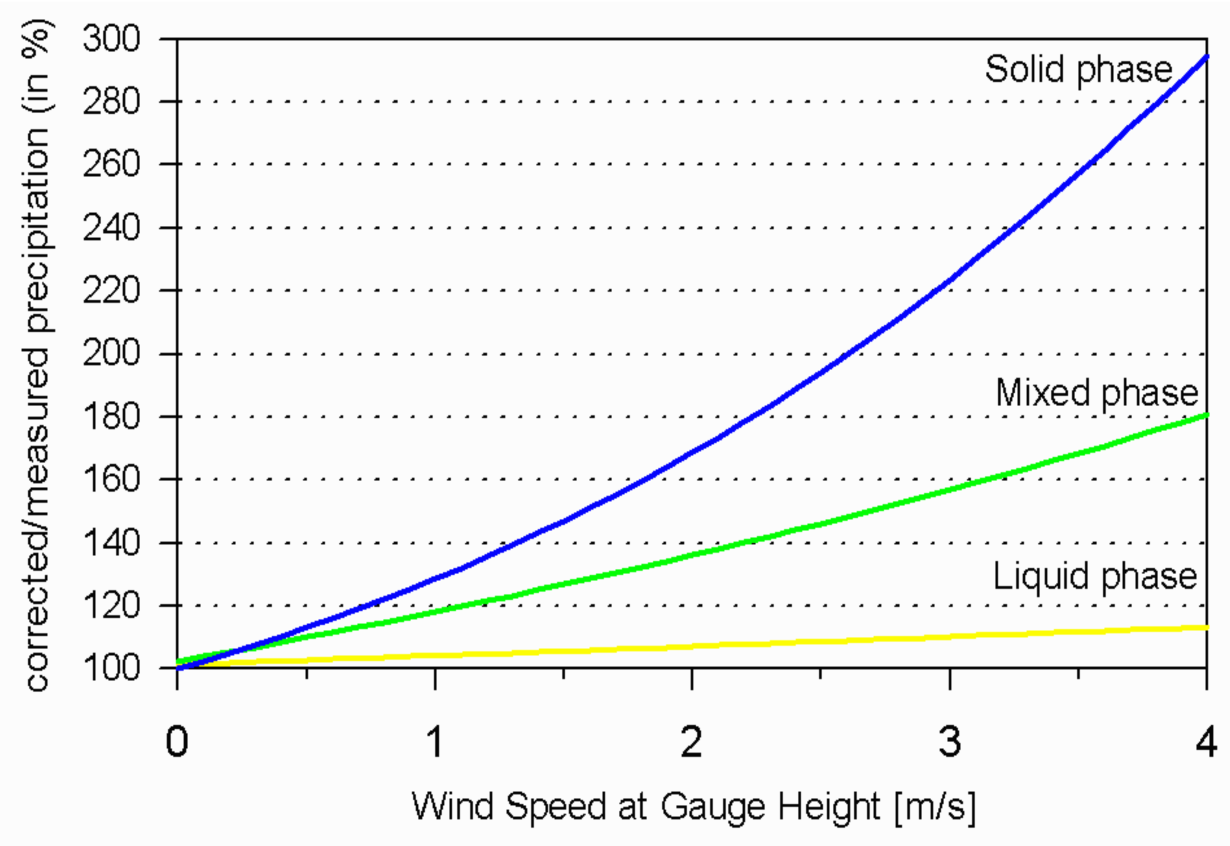
WMO Instruments Comparison Programme

Here: Comparison Site at Barrow/Alaska, June 2002

Systematic gauge measuring error

WMO Solid Precipitation Measurement Comparison Study

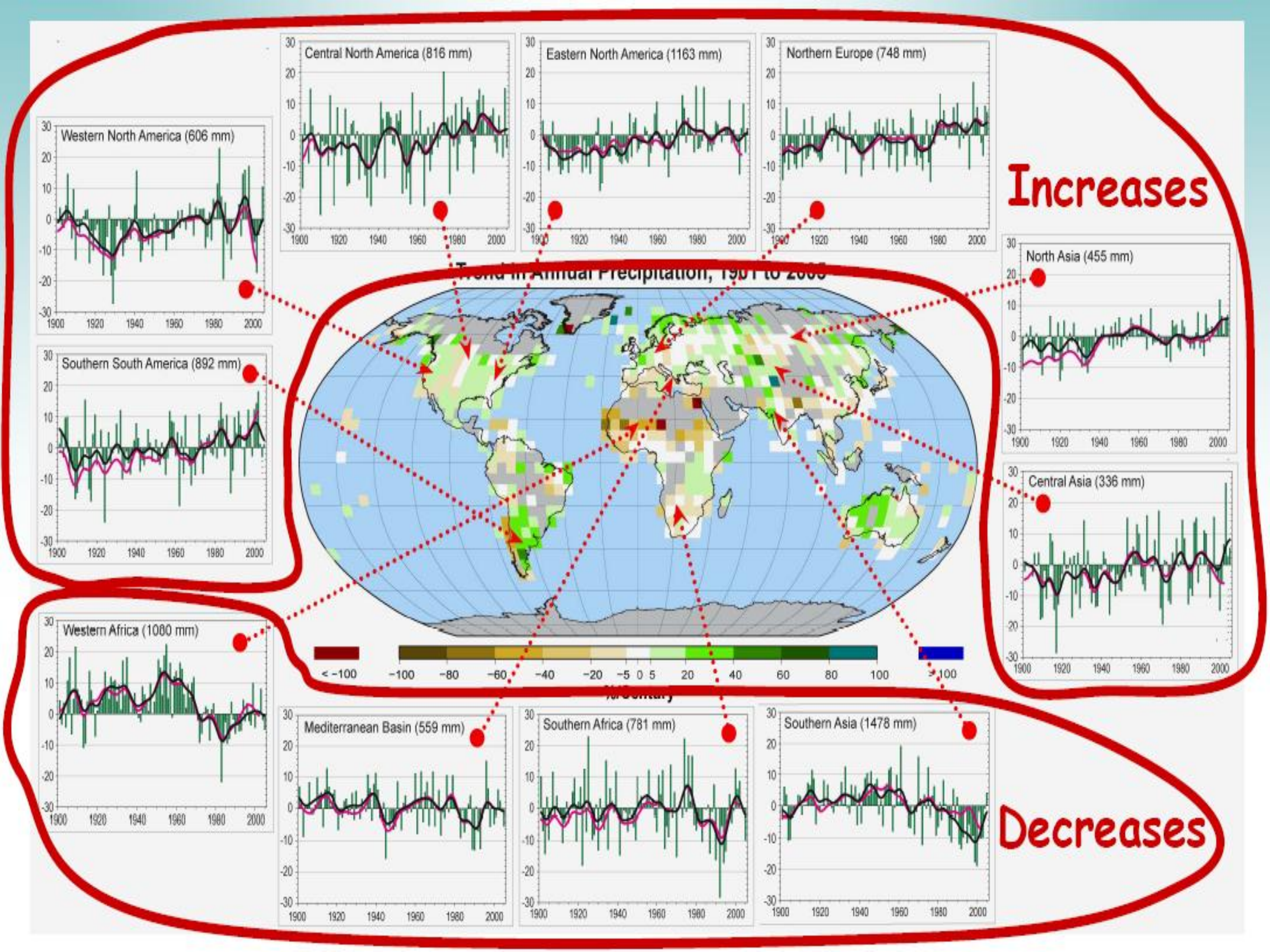
Precipitation phase and wind speed are the most important meteorological parameters for the systematic error



The GPCC has developed a method to estimate wind speed, precipitation phase, air temperature and humidity from synoptic data, which are needed to calculate the bias corrections on a daily "on event" basis.

(Figure: T. Günther in Goodison et al, 1998)

Note that there are also spatial sampling errors and process errors (virga)



Central North America (816 mm)
Eastern North America (1163 mm)
Northern Europe (748 mm)
Western North America (606 mm)
Increases
North Asia (455 mm)
Southern South America (892 mm)
Central Asia (336 mm)
Western Africa (1080 mm)
Mediterranean Basin (559 mm)
Southern Africa (781 mm)
Southern Asia (1478 mm)
Decreases
< -100
-100 -80 -60 -40 -20 -5 0 5 20 40 60 80 100
> 100

Precipitation patterns are changing on global scales…

The Perfect Ocean for Drought

Martin Hoerling[1]* and Arun Kumar[2]

SCIENCE VOL 299 31 JANUARY 2003

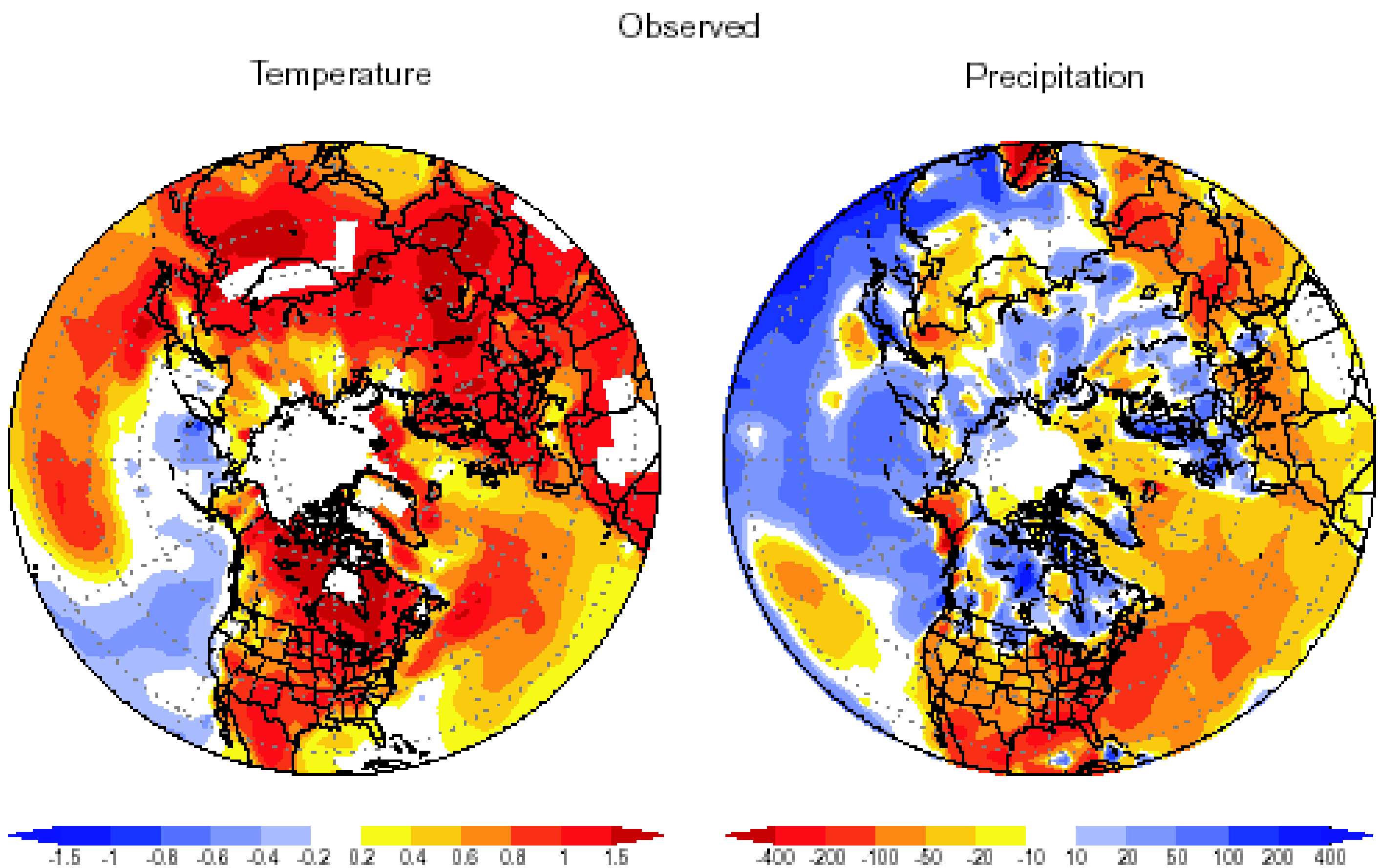
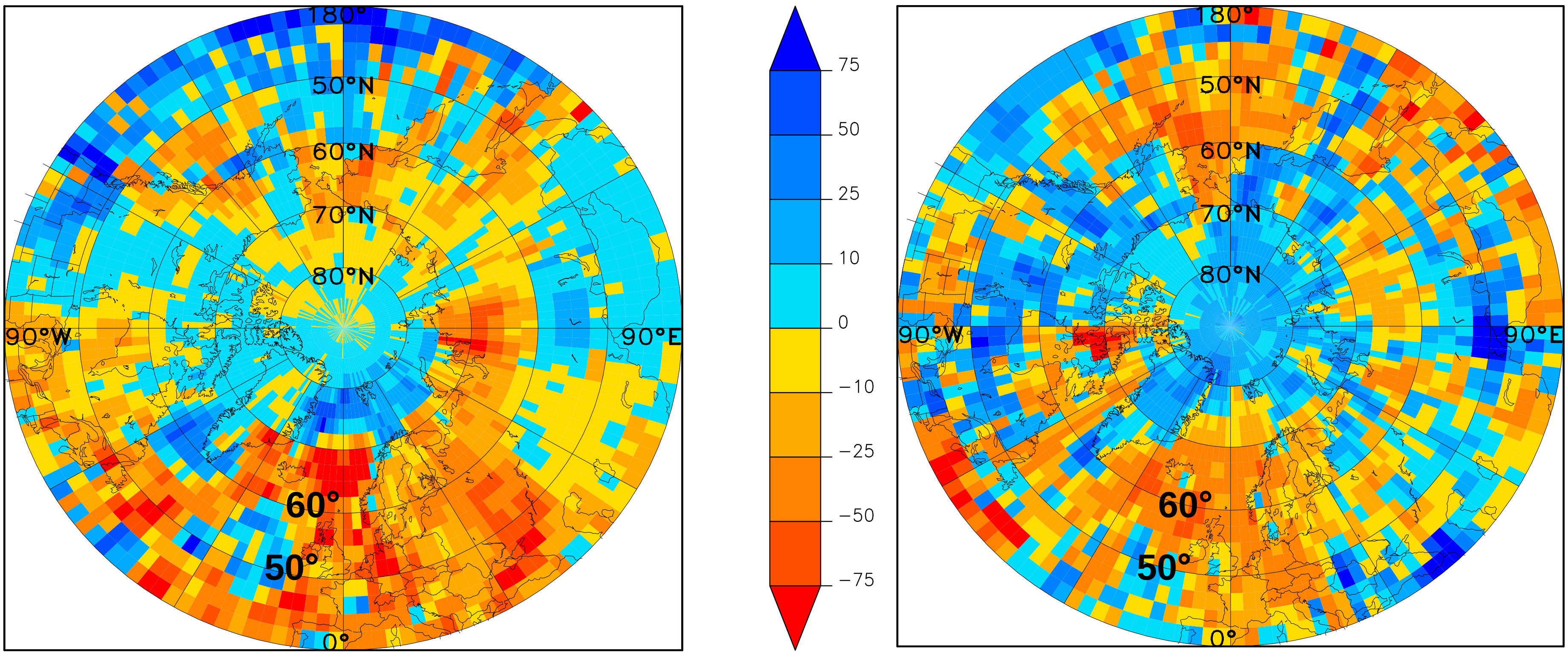


Fig. 1. Observed, annually averaged surface temperature (**left**) and precipitation (**right**) anomalies during the 4-year period June 1998–May 2002. Temperature departures are degrees Celsius

The Arctic Hydrological Cycle
of NWPM Reanalysis ERA-40

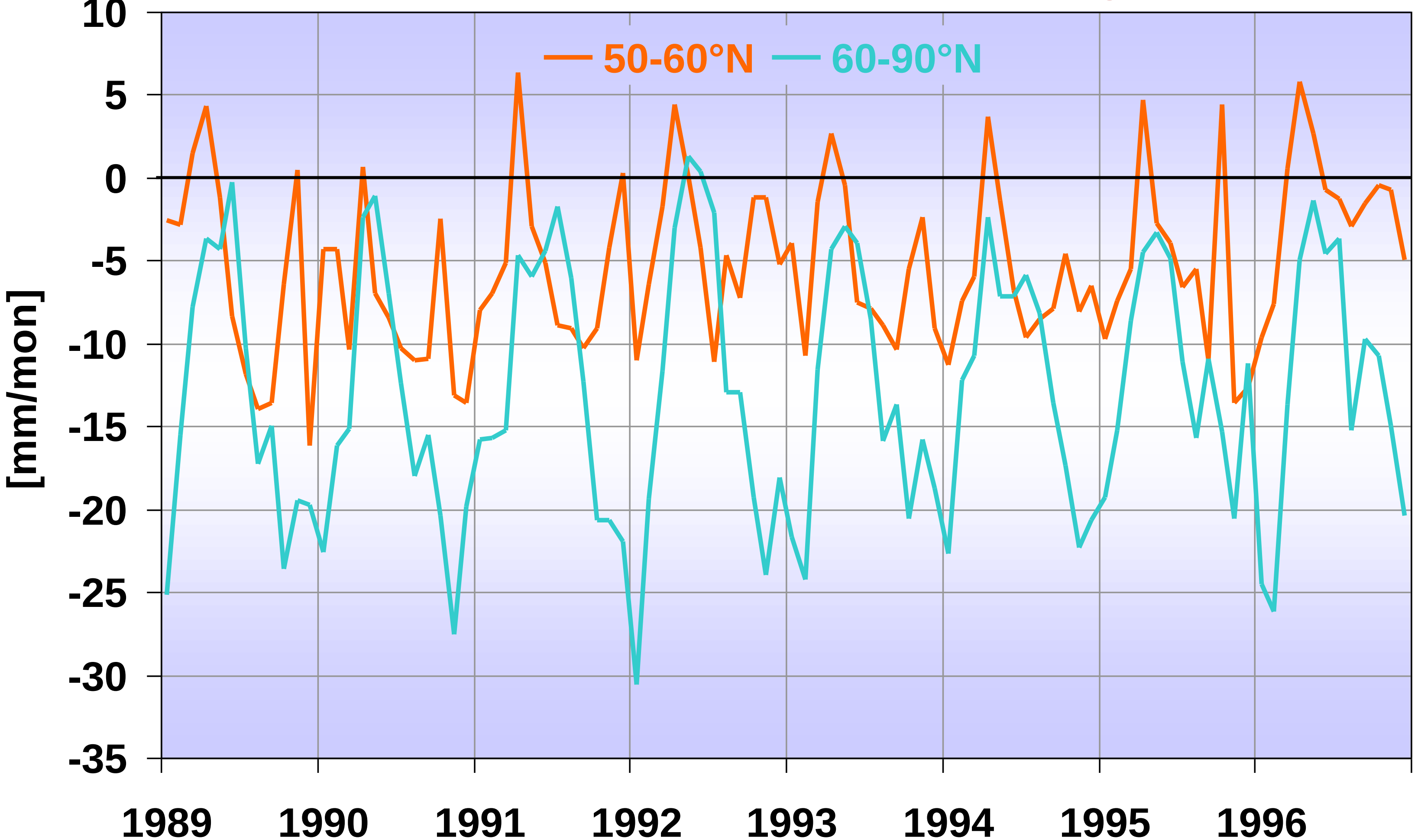
Differences of precipitation ERA-40 minus GPCP V2 Sat-Gauge

January 1995 **mm/mon** **July 1995**

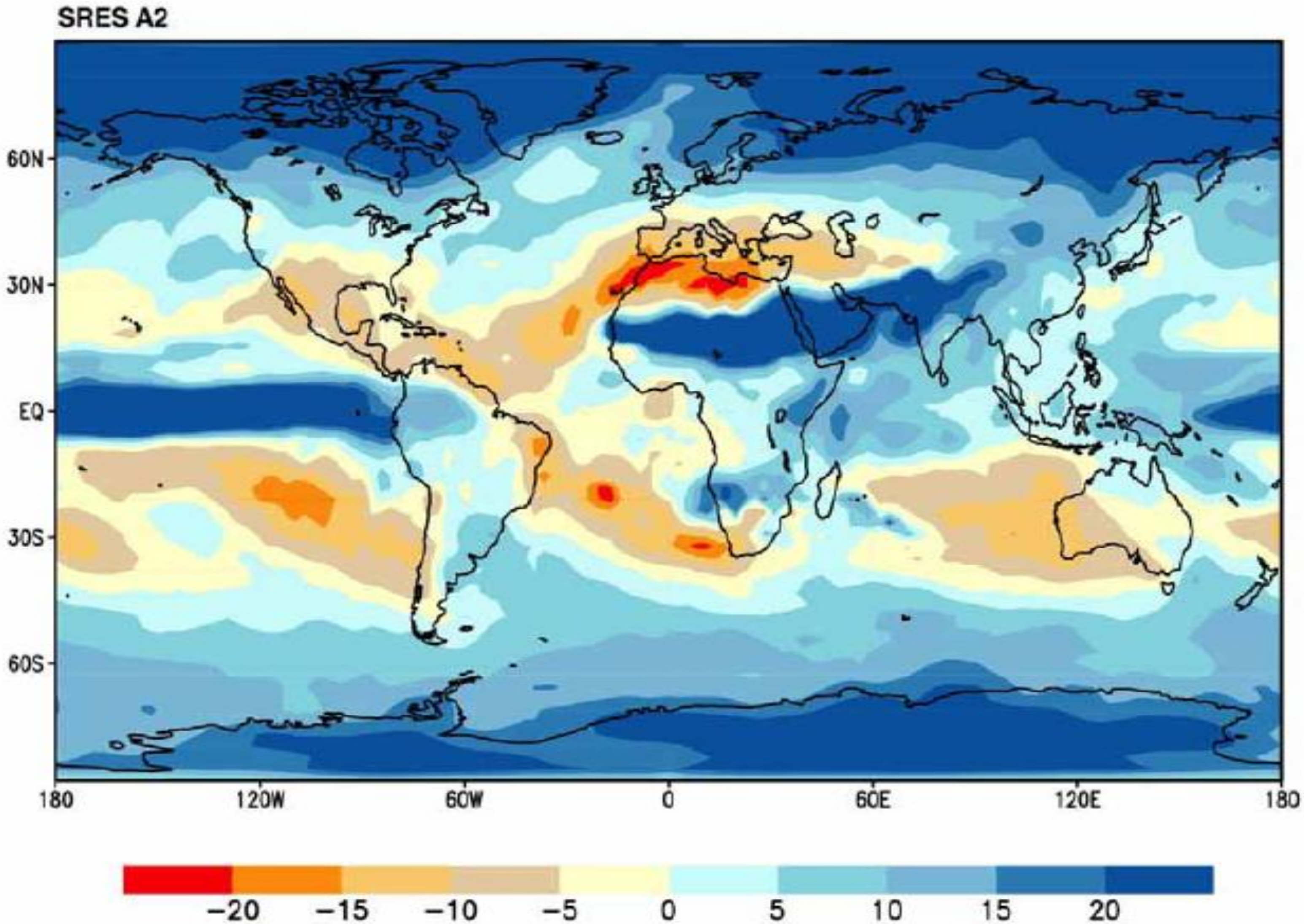


# of NWPM Reanalysis ERA-40

Differences of zonal area-mean precipitation for ERA-40 minus GPCP V2 Sat-Gauge

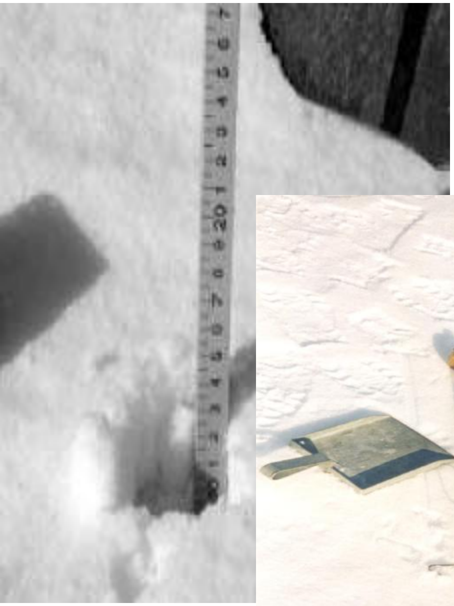


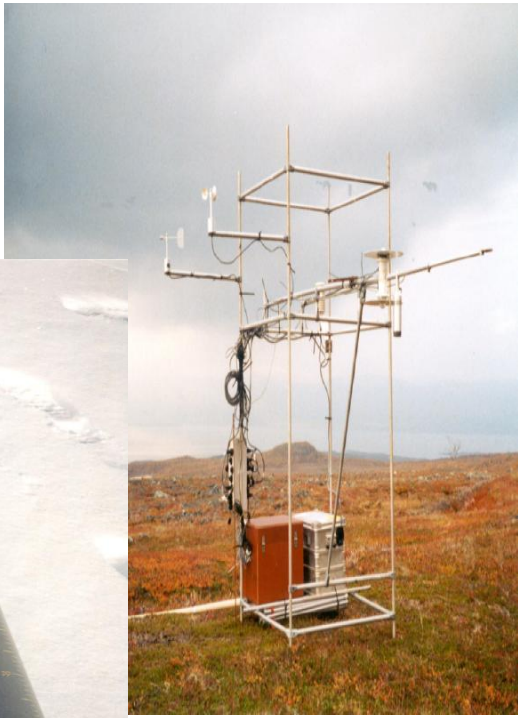
Annual mean precipitation change: 2071 to 2100 Relative to 1990

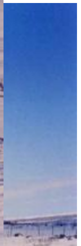


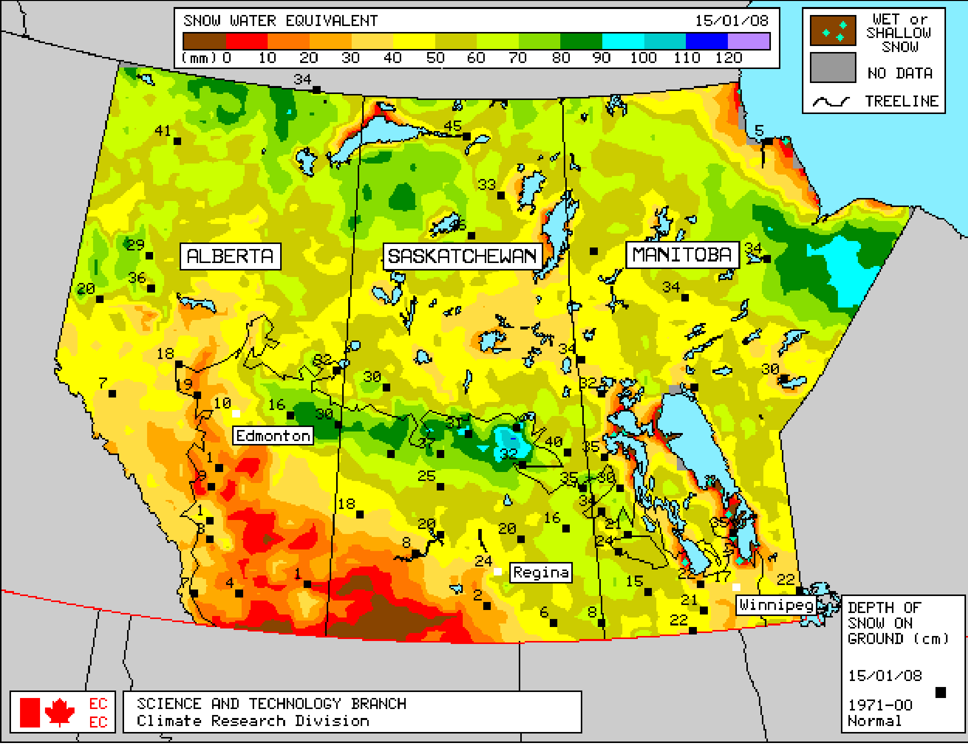
SNOW COVER

- High albedo (ages, dust, vegetation interaction)
- Good thermal insulator
- Density increases with time
- Complex layering, melting, crystal growth, density variations, etc.
- **Snow Water Equivalent (SWE)** difficult to measure
- **Snow cover or extent** common from VIS/IR remote sensing
- **Snow depth** can be easily measured
- **Snow density** useful for modeling and remote sensing









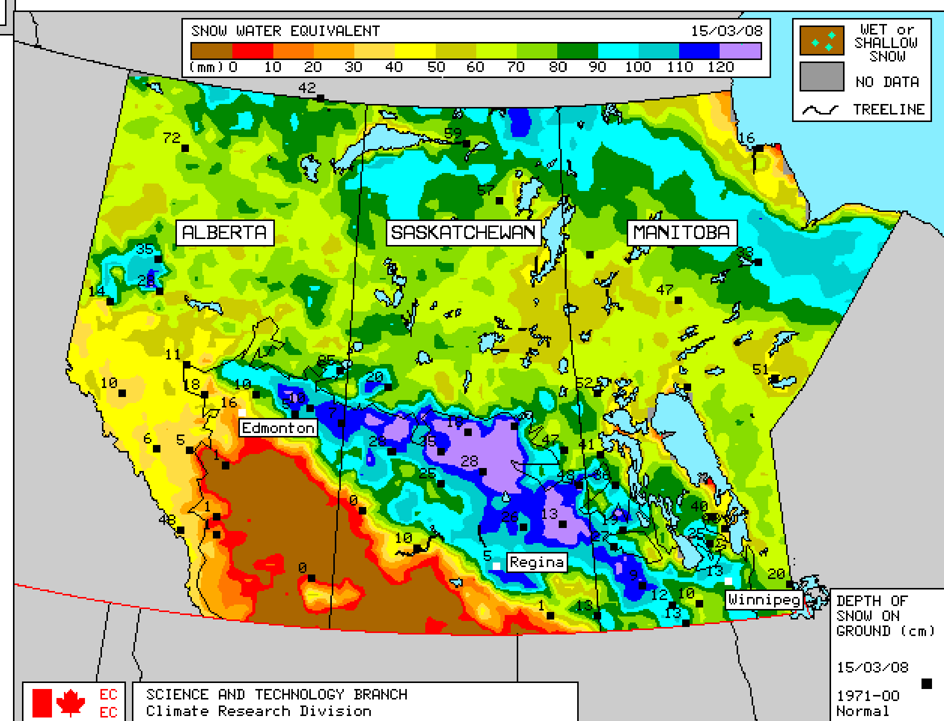
Example:

Snow Water Equivalent

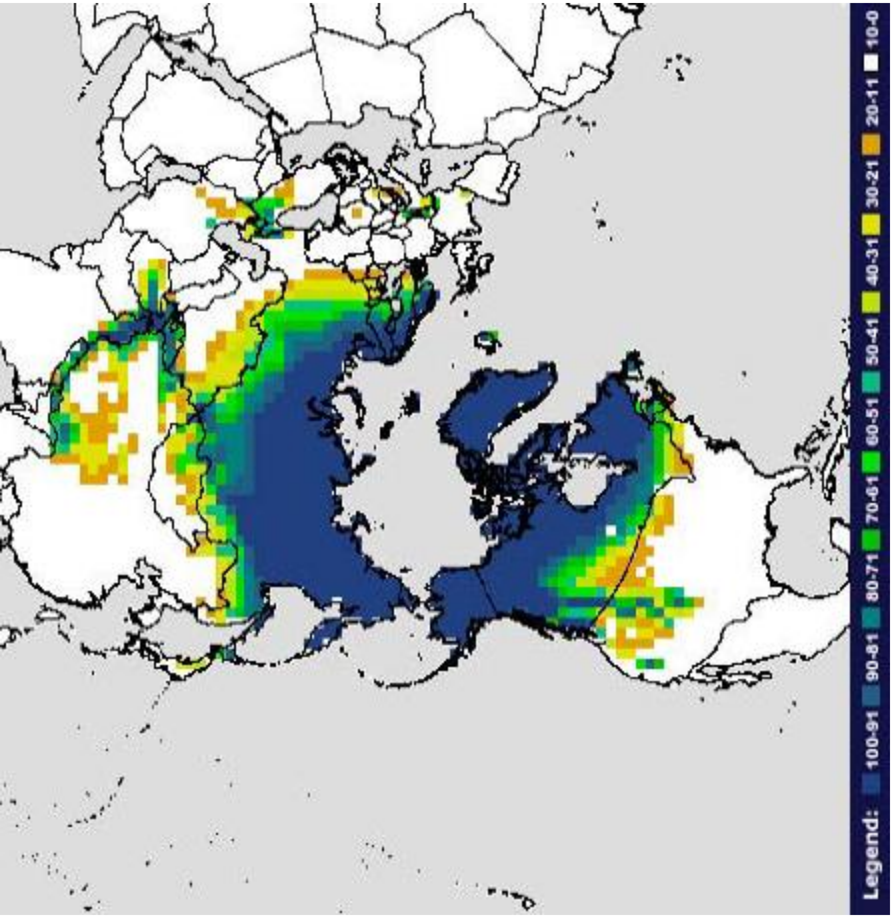
SWE derived from AMSR-E for Western Canada

Issues for GCW?

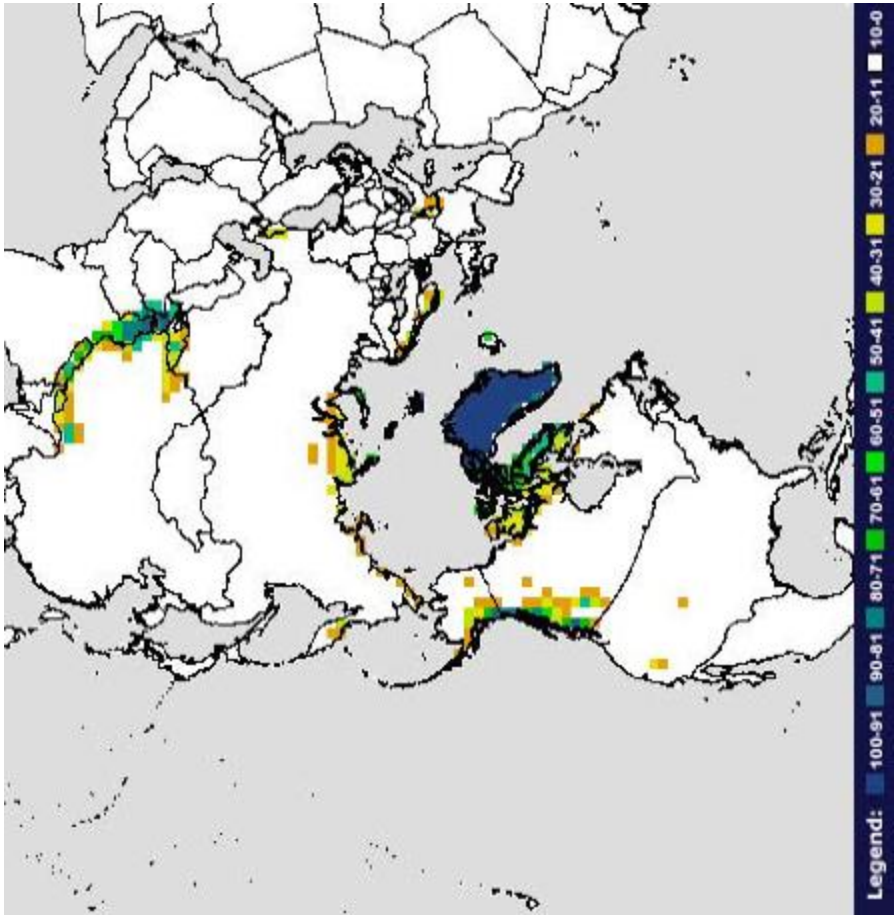
- evaluation of the product
- how consistent is the derived SWE
- evaluation of the algorithms
- transferability of algorithms
- usefulness of the product
- sustainability of product development and production
- when will this product be ready to transfer from research to operations



Snow cover in April (1966-1999)

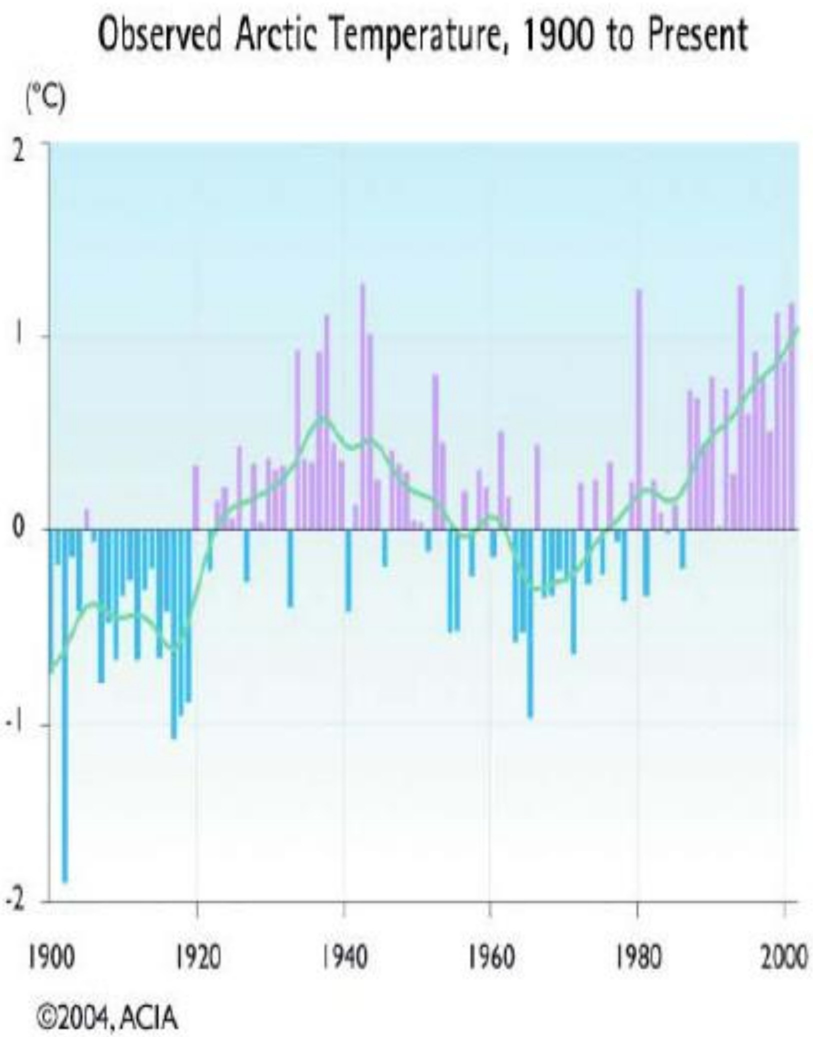


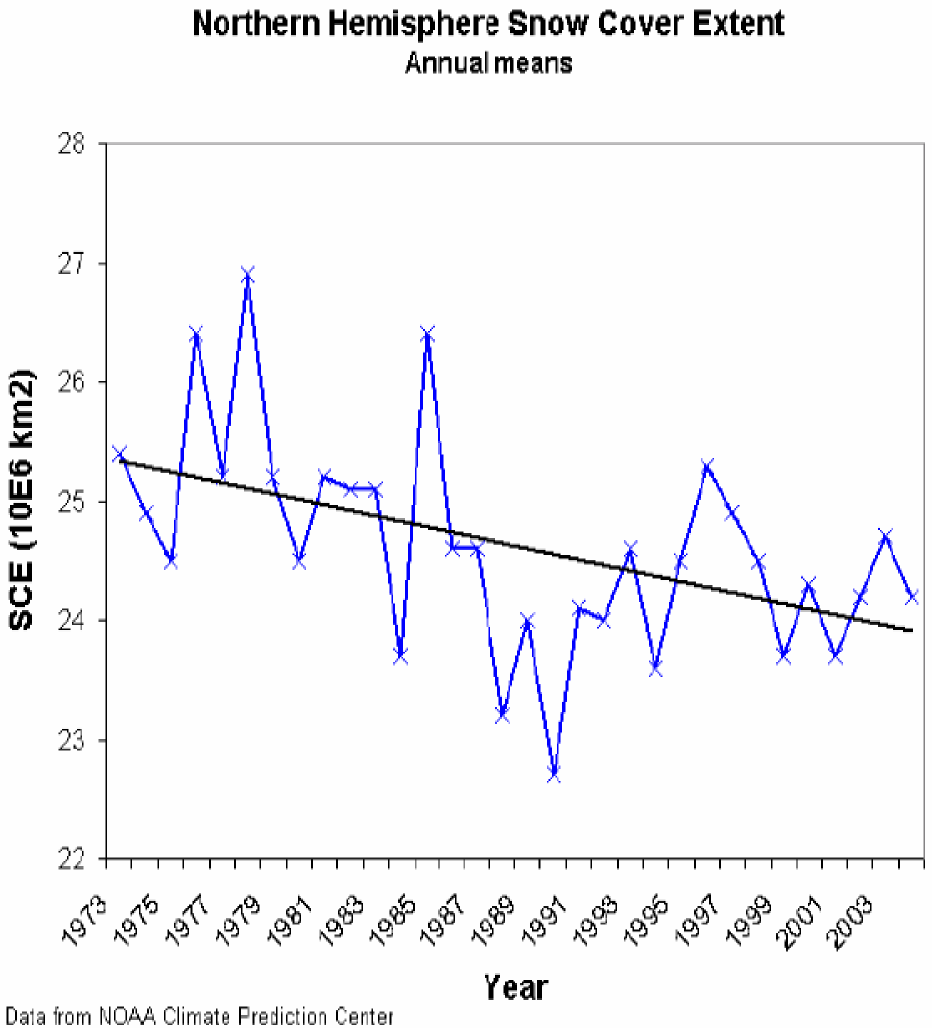
Snow cover in July (1966-1999)



Source: Rutgers University Global Snow Lab

How is Arctic snow cover changing?





Impact on Ski Industry

- In the US skiing is a $5B industry
- 2006 saw a 78% decline in skiers visiting the pacific northwest US
- Ski Seasons have shortened by 1 day/year for the last 20 years
- Many European ski resorts below 1800 m (6000 ft) will close
- 50 to 90% of Alpine glaciers will be gone by 2100
- Some resort to snowmaking
  - Expensive
  - Requires lots of water
  - Requires lots of energy
- In New Mexico, many ski areas can’t open until after Xmas

Permafrost

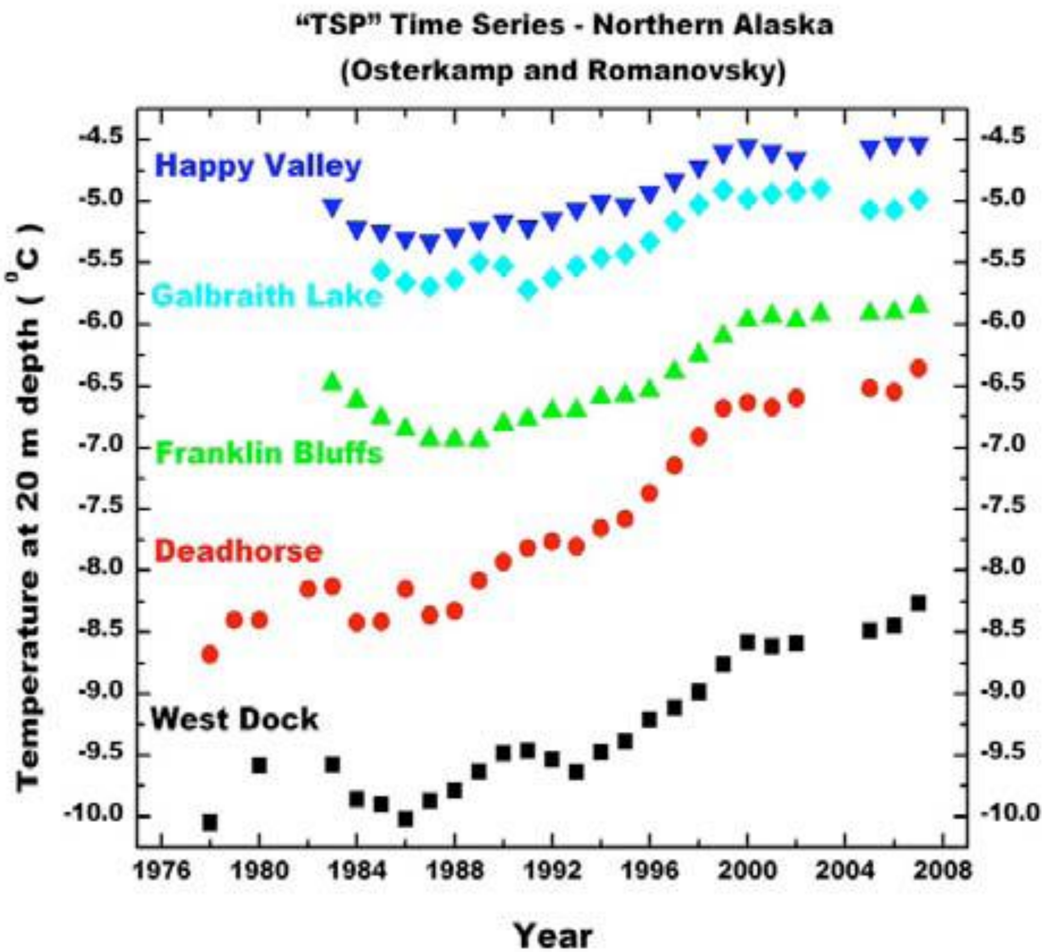
• The discontinuous permafrost region, currently within 1-2 degrees of thawing, will see most dramatic melt

• Where ground ice contents are high, this permafrost degradation will have associated physical impacts.

• Biggest concern are soils with the potential for instability upon thaw (thaw settlement, creep or slope failure). Such instabilities may have implications for the landscape, ecosystems, and infrastructure. (GSC 2002)

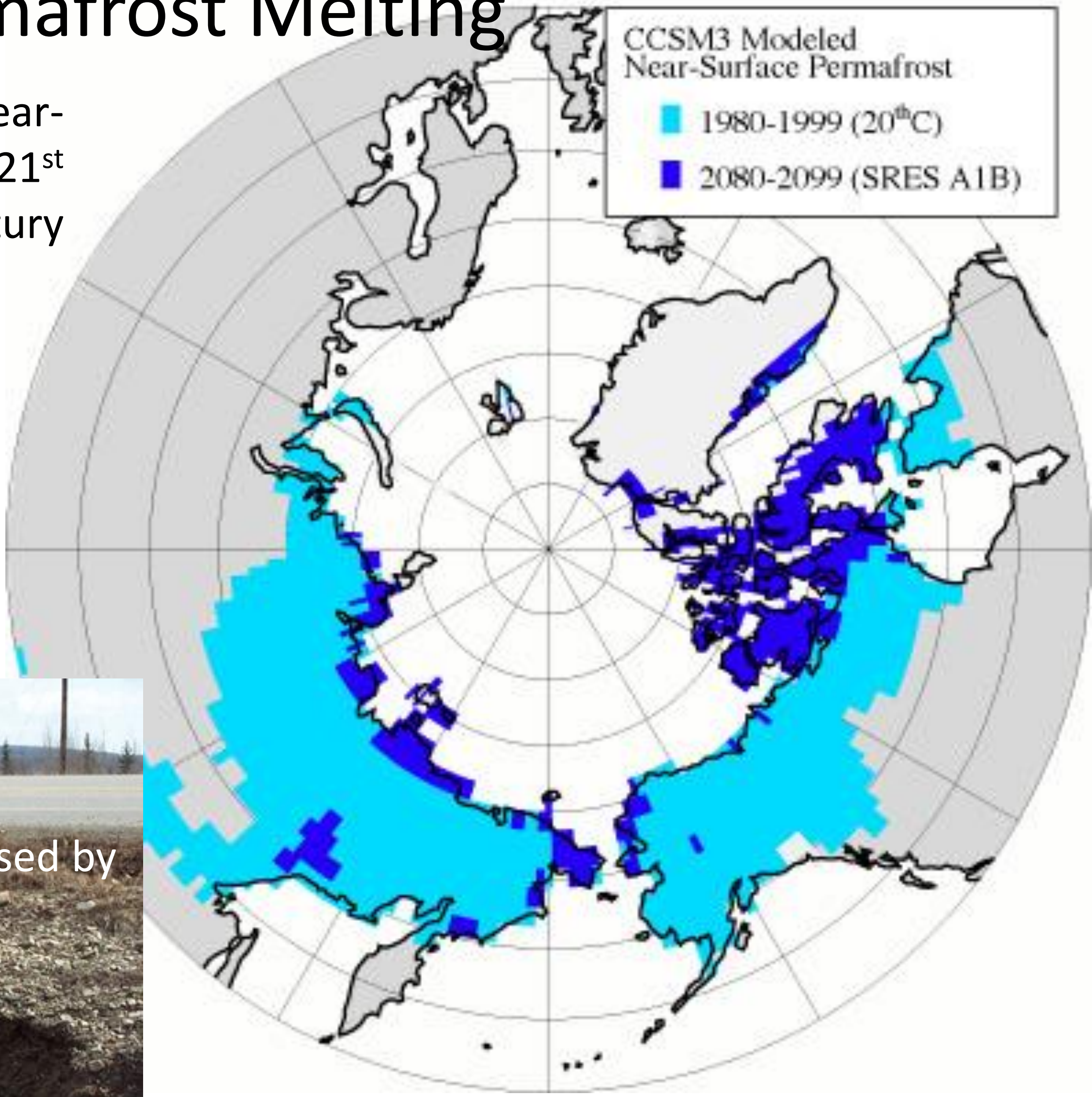
• Thawing of permafrost is likely to release CO2 and CH4 that have been trapped in the frozen soil, further contributing to global warming.

Changes since 1978 in permafrost temperatures at 20 m depth (updated from Osterkamp 2003). Northern Alaska. ARC 2008.

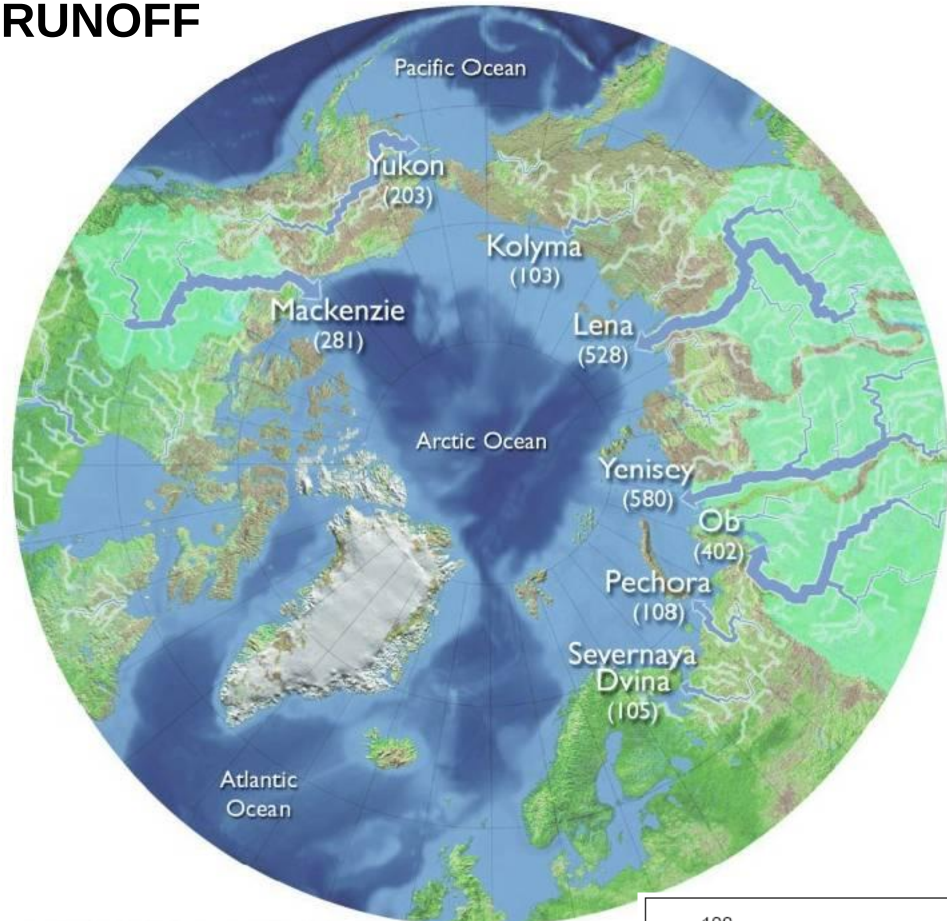


One Projection of Permafrost Melting

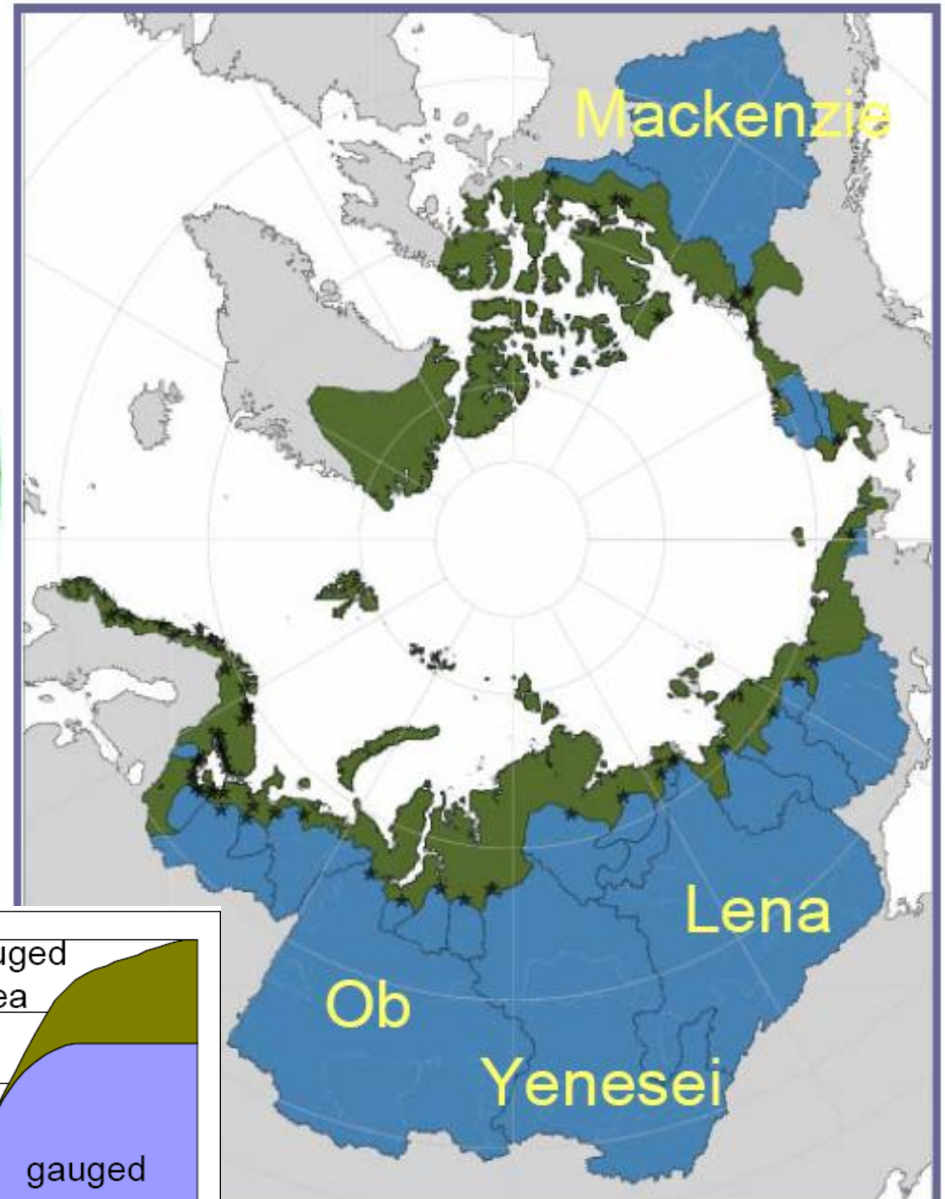
Projected reductions in near-surface permafrost in 21st century

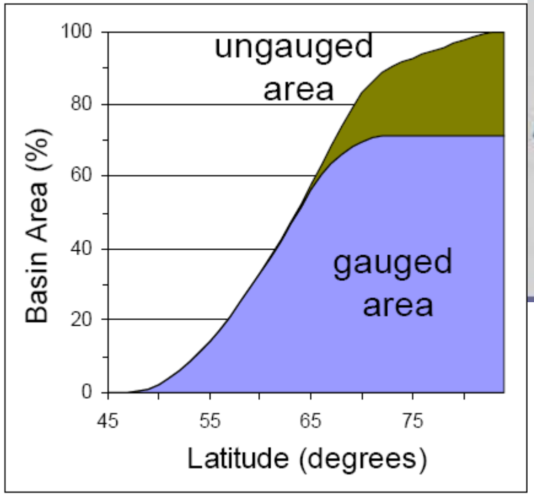


RUNOFF



©2004, ACIA / Map ©Clifford Grabhorn



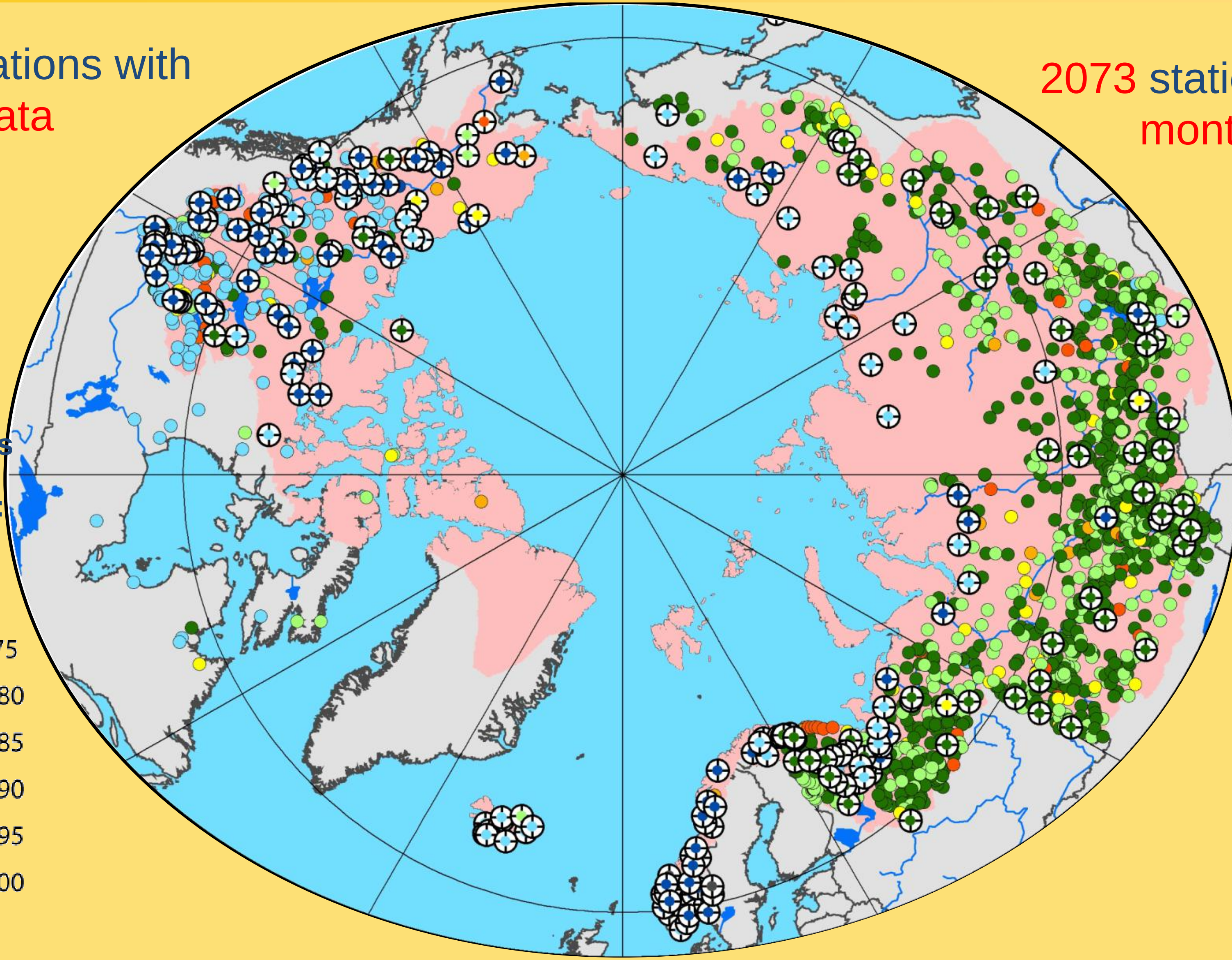


Arctic Runoff Data Base (ARDB)

of the Global Runoff Data Centre

270 stations with daily data

2073 stations with monthly data



time series end for daily data:

daily data

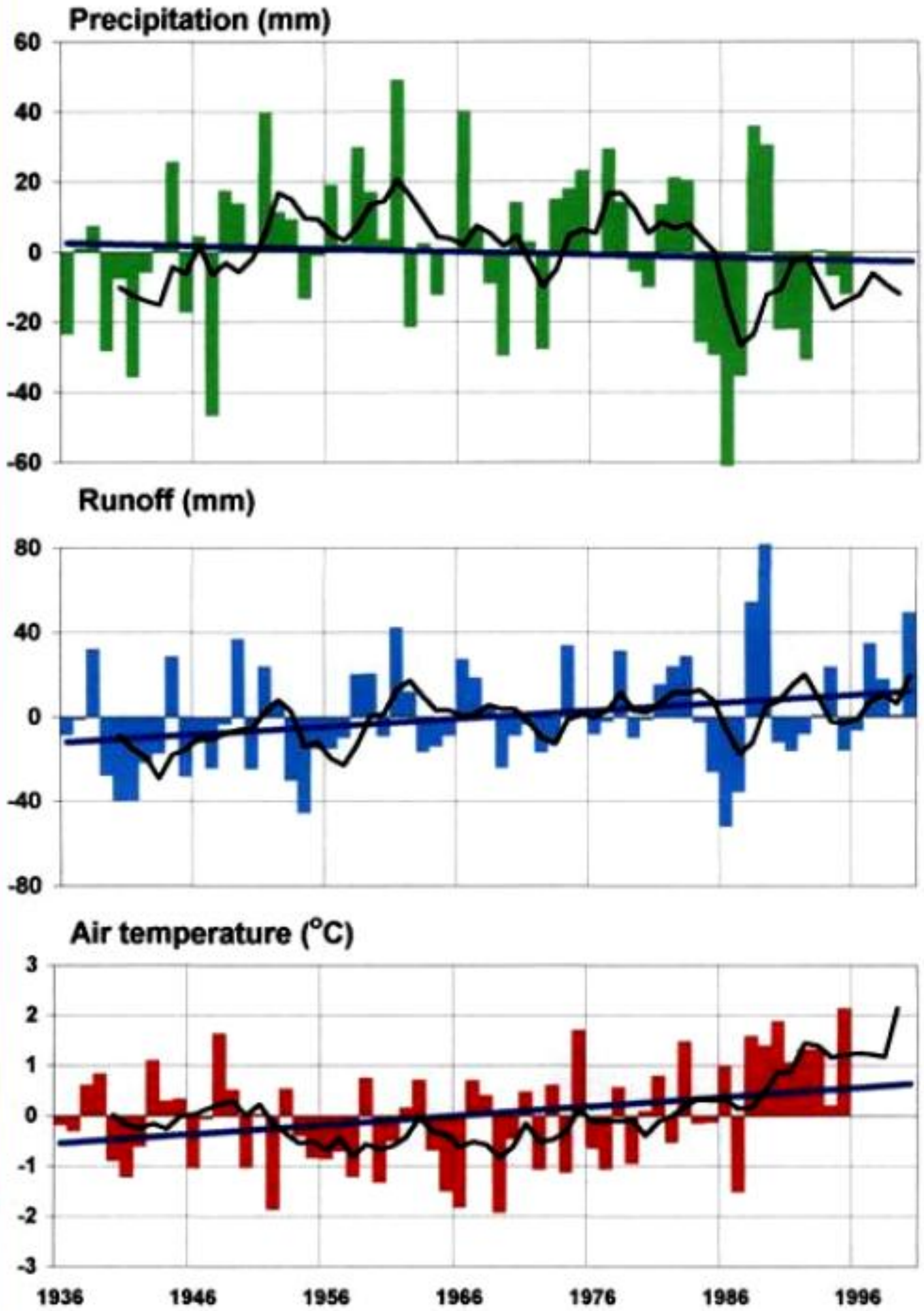
- < 1970
- 1971 - 1975
- 1976 - 1980
- 1981 - 1985
- 1986 - 1990
- 1991 - 1995
- 1996 - 2000
- > 2000

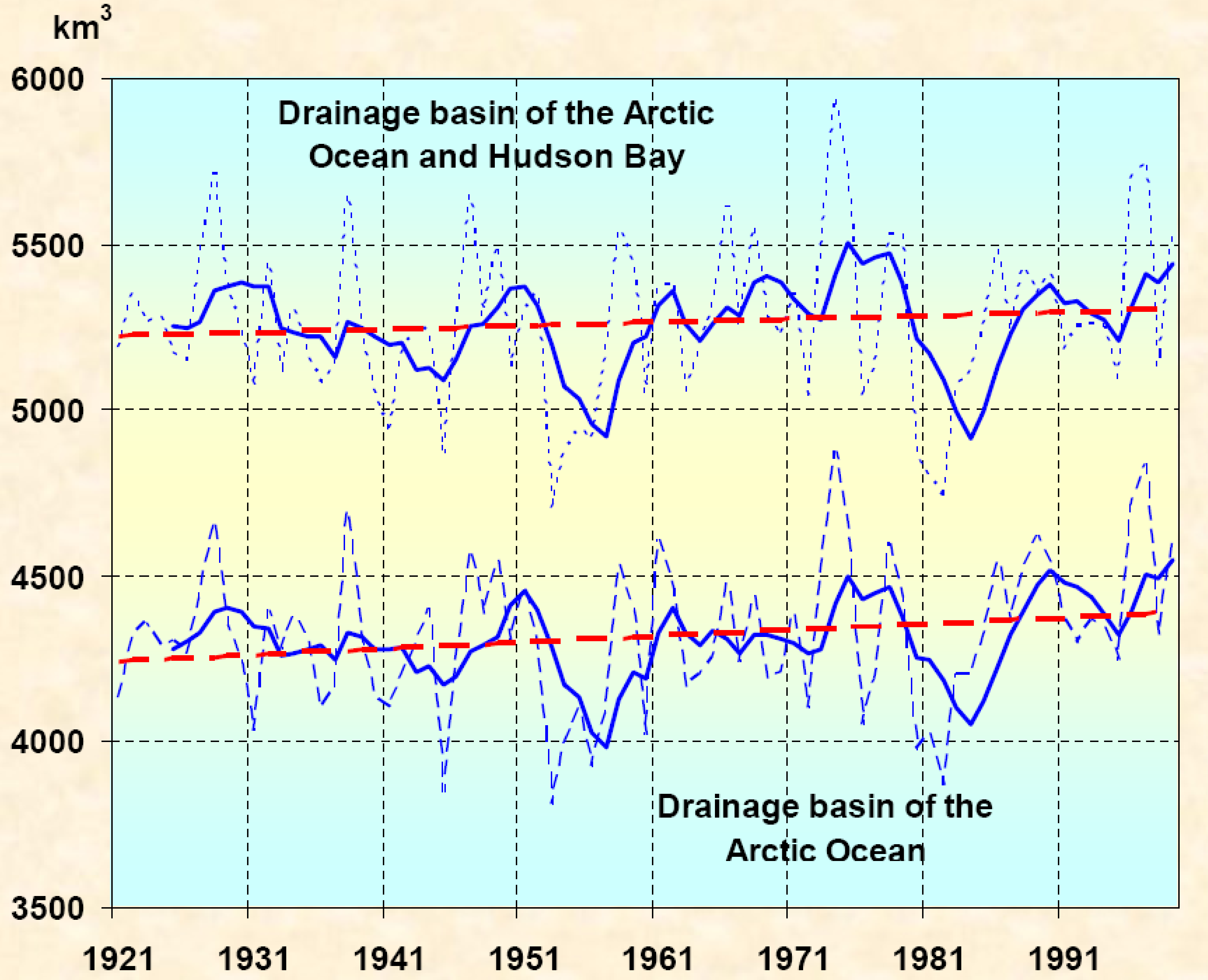
time series end for monthly data:

monthly data

- < 1970
- 1971 - 1975
- 1976 - 1980
- 1981 - 1985
- 1986 - 1990
- 1991 - 1995
- 1996 - 2000
- > 2000

Long-term variations in air temperature, precipitation and runoff in the Lena river basin

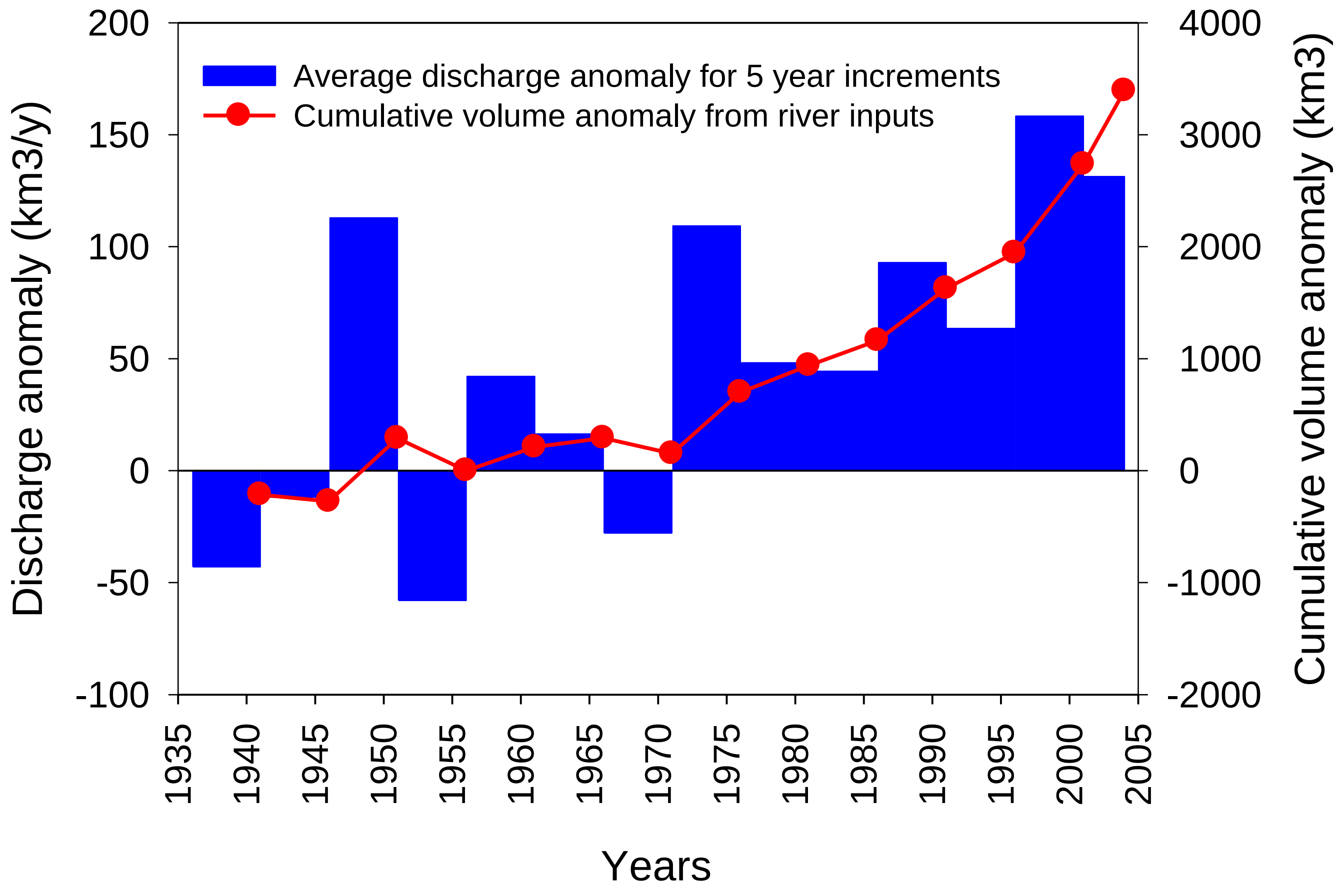




km3
6000
5500
5000
4500
4000
3500
1921
1931
1941
1951
1961
1971
1981
1991
Drainage basin of the Arctic Ocean and Hudson Bay
Drainage basin of the Arctic Ocean

Change in combined discharge from the 6 largest Eurasian arctic rivers

Yenisey, Ob', Lena, Kolyma, Severnaya Dvina, Pechora

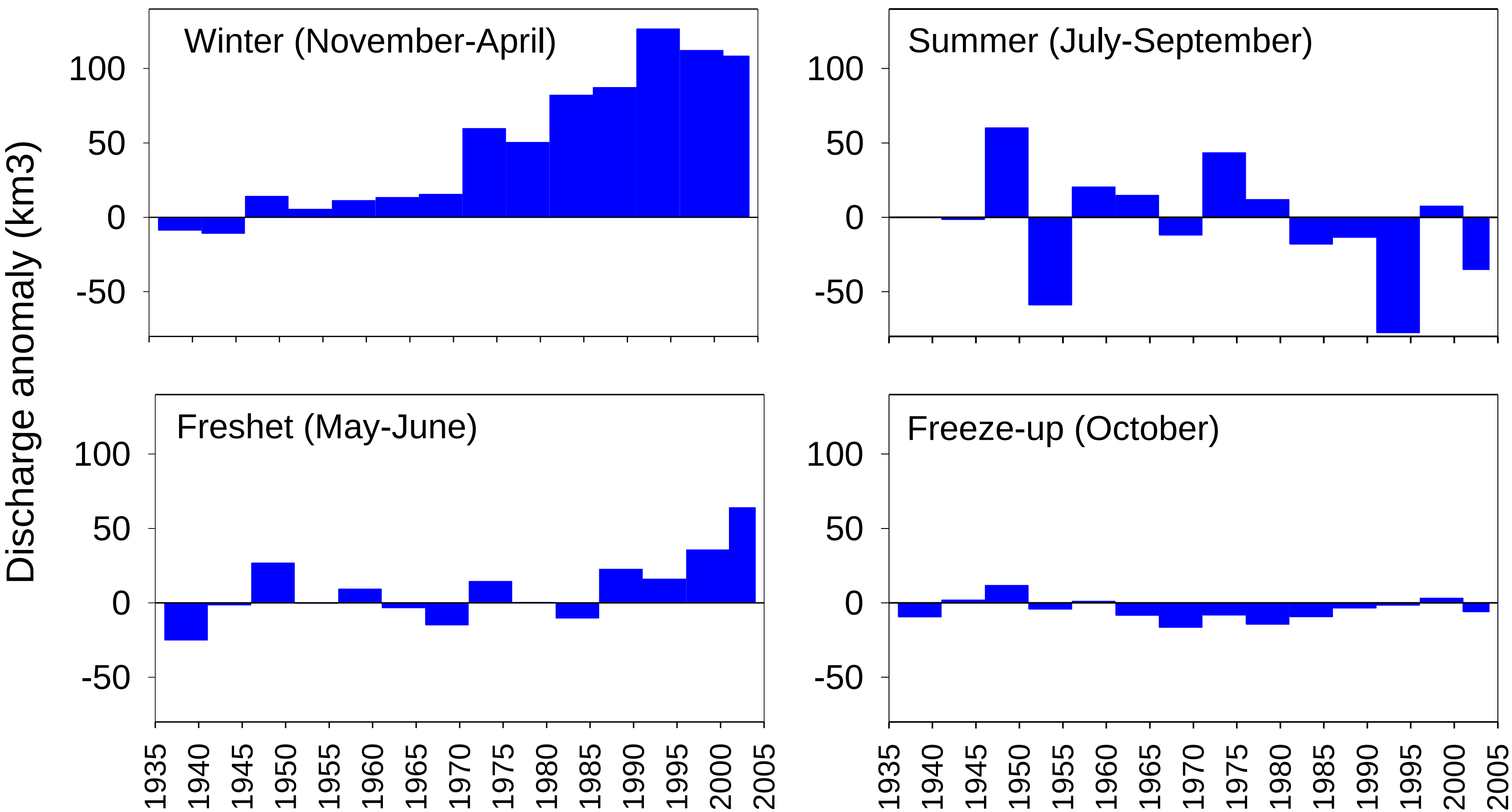


*Anomalies are relative to average discharge from 1936 to 1955

http://ecosystems.mbl.edu/partners/

Change in the seasonality of combined discharge from the 6 largest Eurasian arctic rivers

Yenisey, Ob', Lena, Kolyma, Severnaya Dvina, Pechora

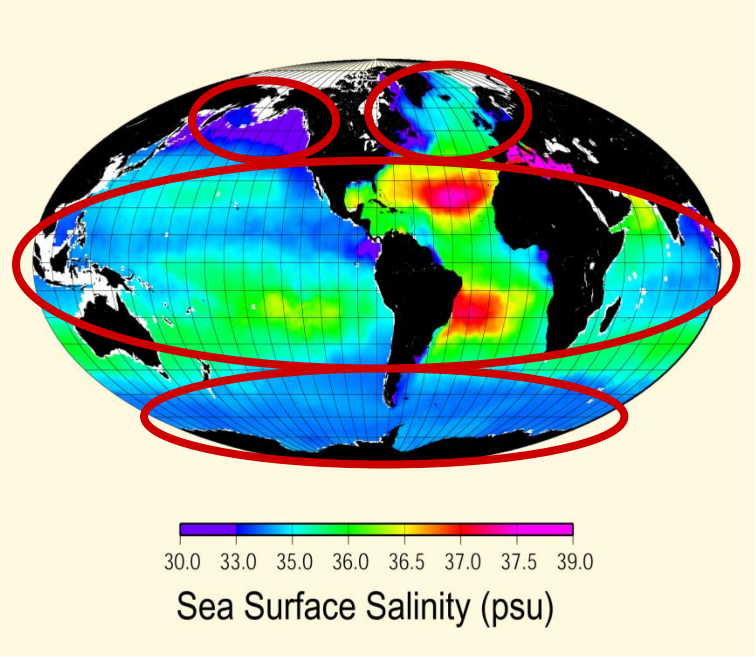


Average discharge anomaly for 5 year increments

*Anomalies are relative to average discharge from 1936 to 1955

http://ecosystems.mbl.edu/partners/

Salinity changes are the fingerprint of increasing evaporation from the low latitude oceans.....



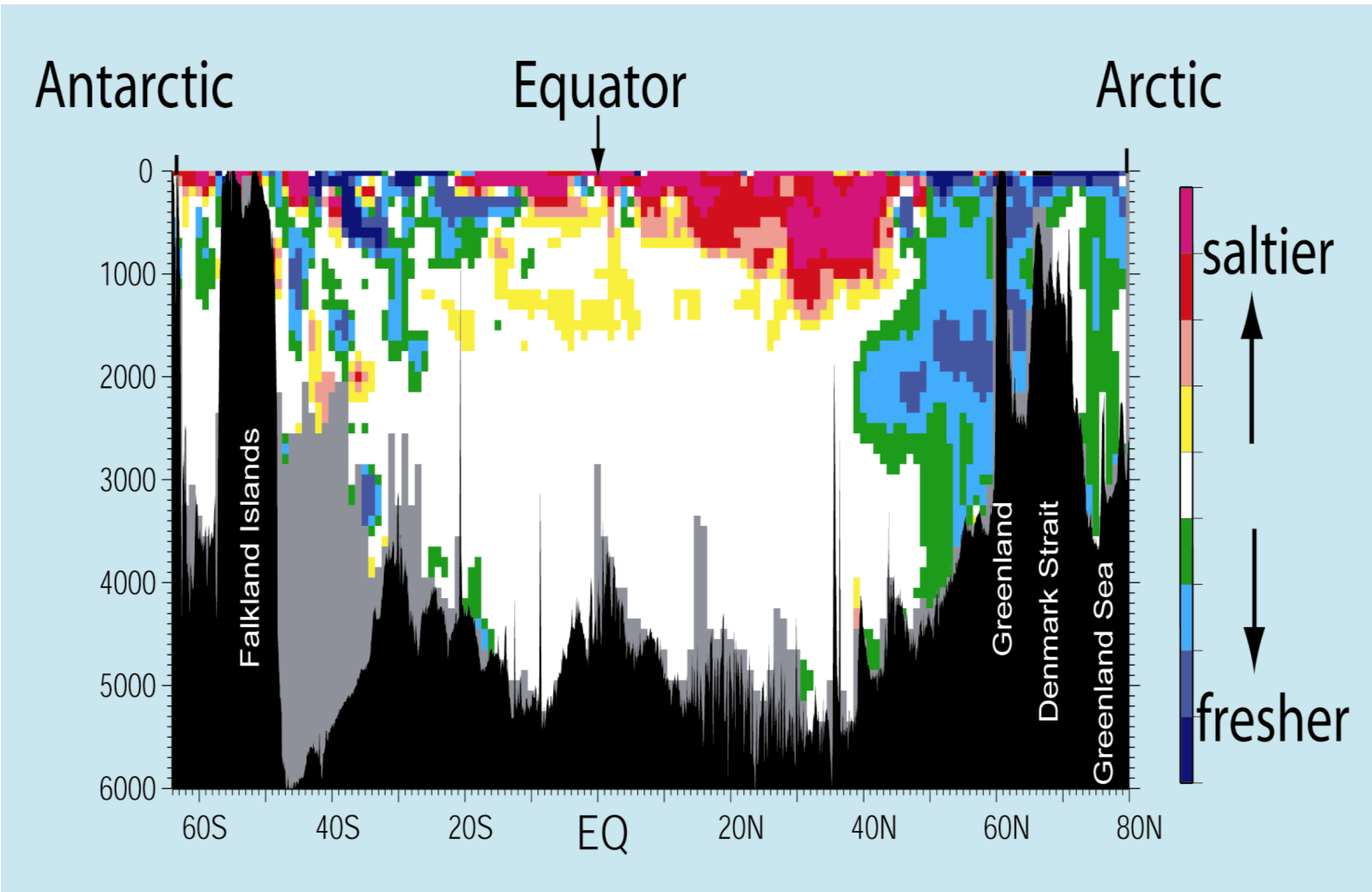
Low latitude surface waters have become markedly more saline

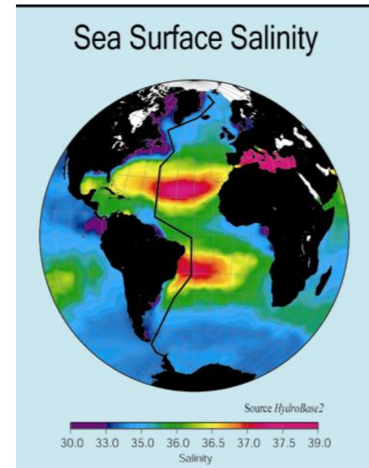
Water masses formed at high latitudes have become fresher

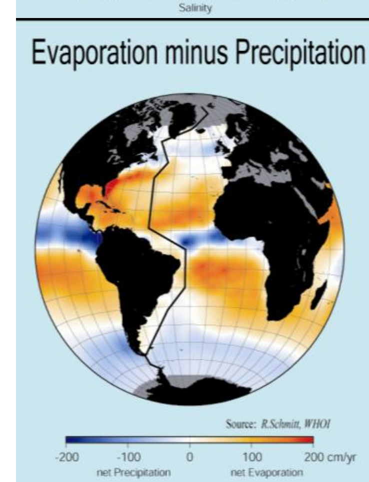
... and freshwater being added to the oceans at high latitudes.

Atlantic Ocean Salinity Changes

1990s compared to 1960s



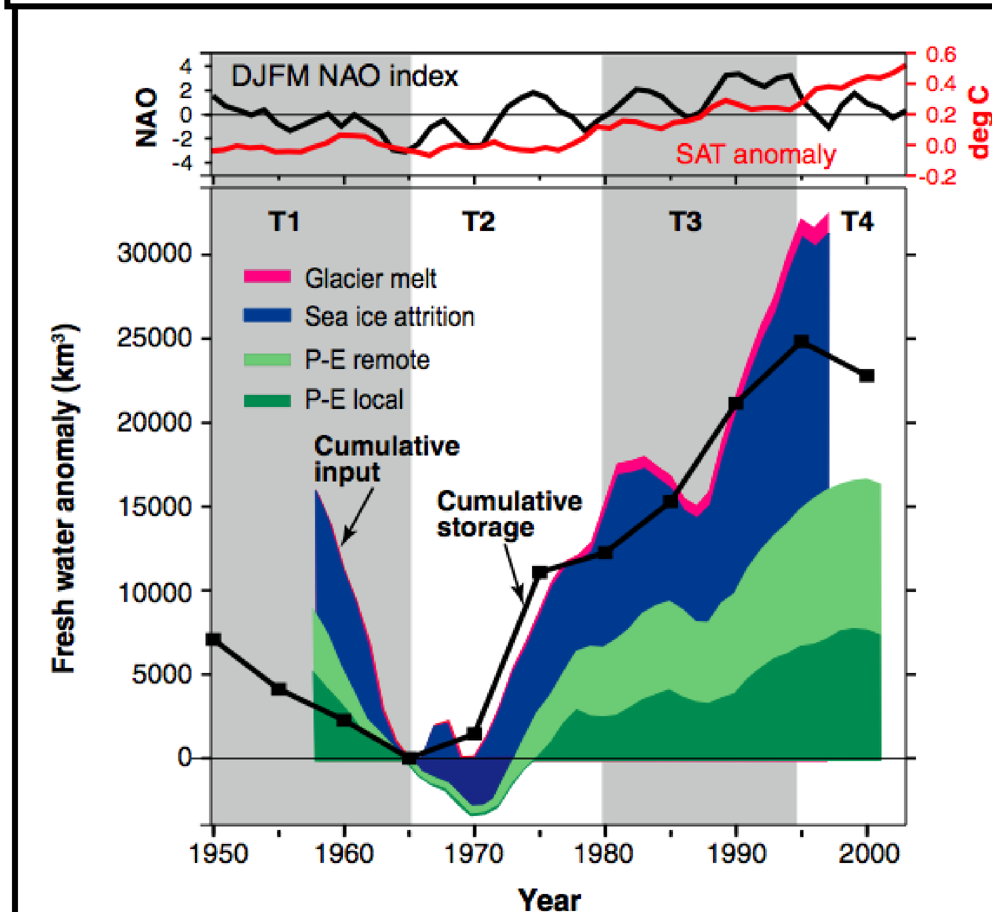


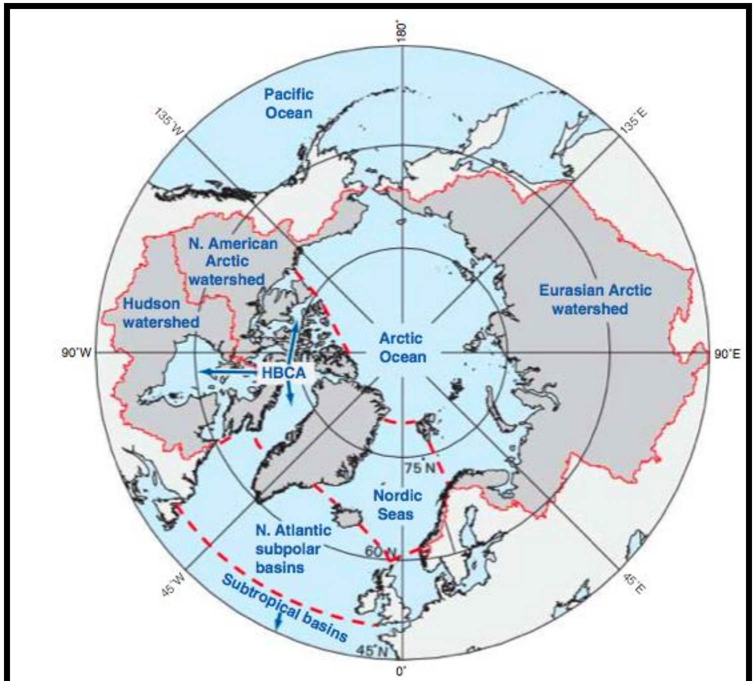


from Curry *et al*. *Nature* (2003)

Scientists winning the *shell game* of where ocean-scale freshwater increases come from and how they redistribute once they enter the high north

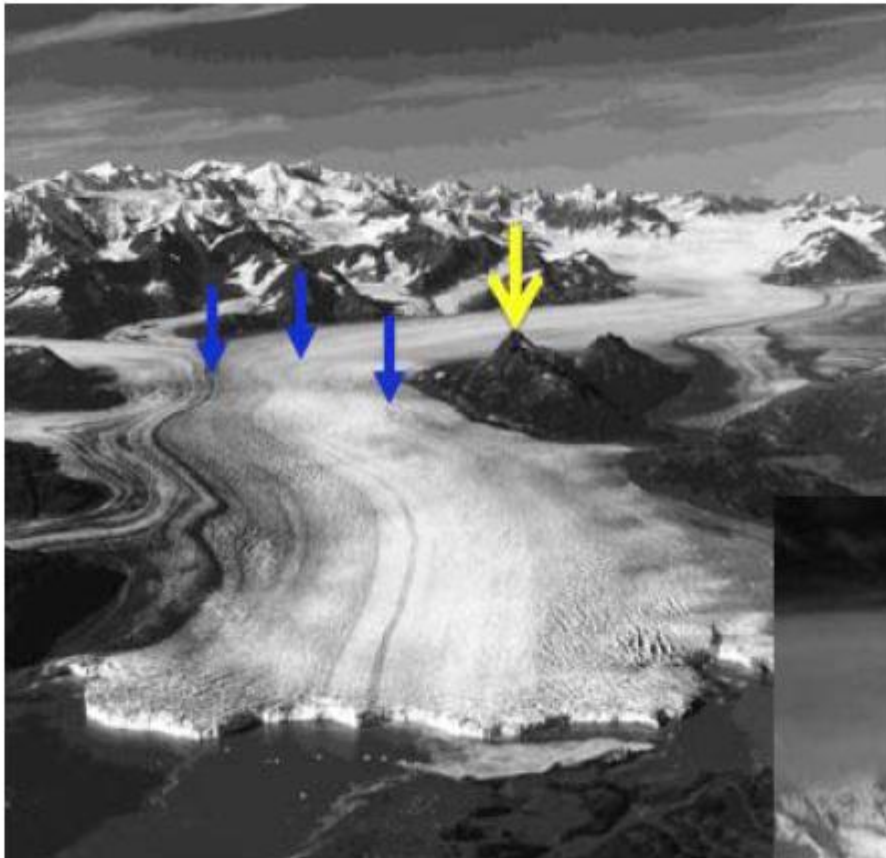
Fresh Water Sources & Storages in Nordic Seas, Sub-Arctic, Sub-Tropical Deep Atlantic





Peterson et al. 2006

GLACIERS



Columbia Glacier, Alaska

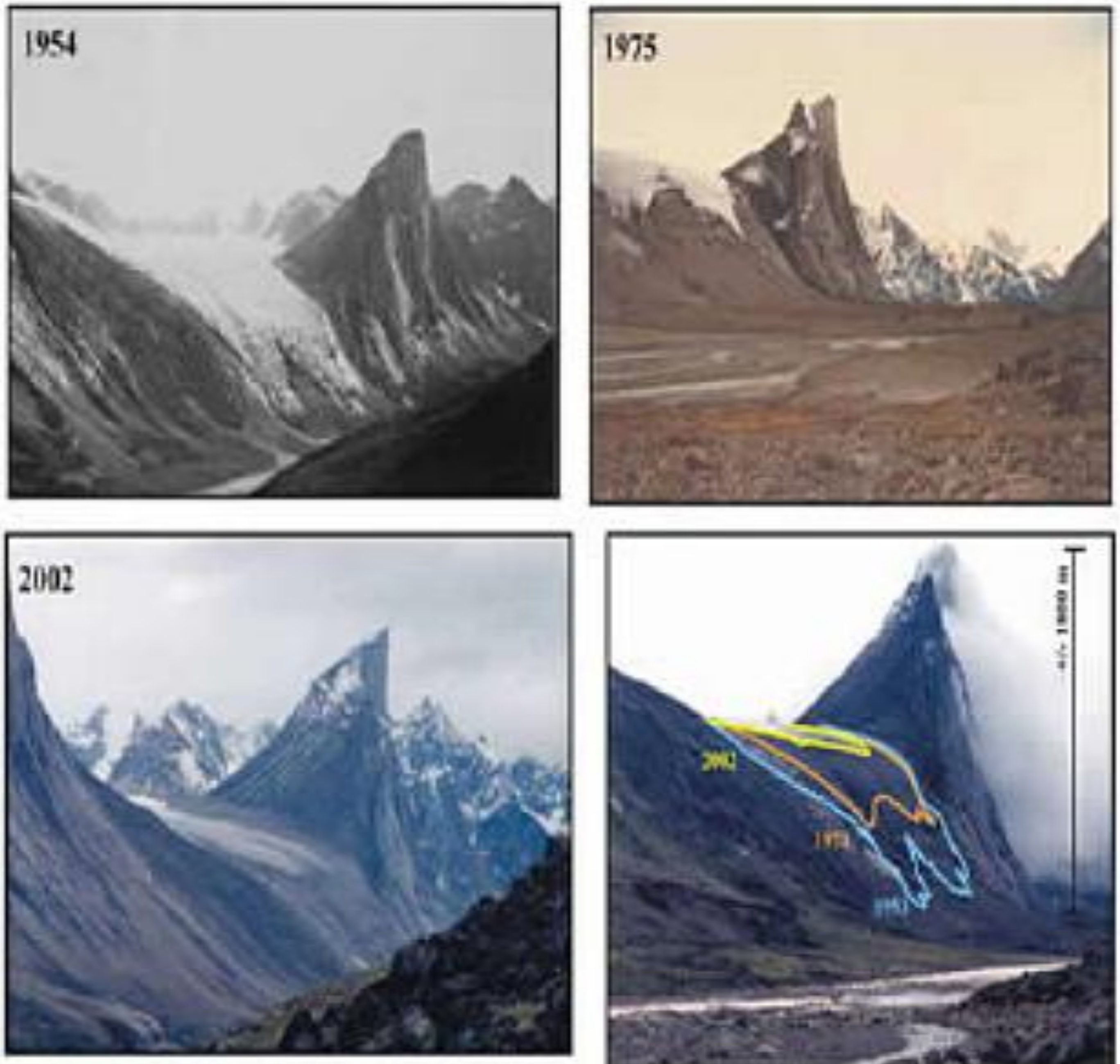
2005

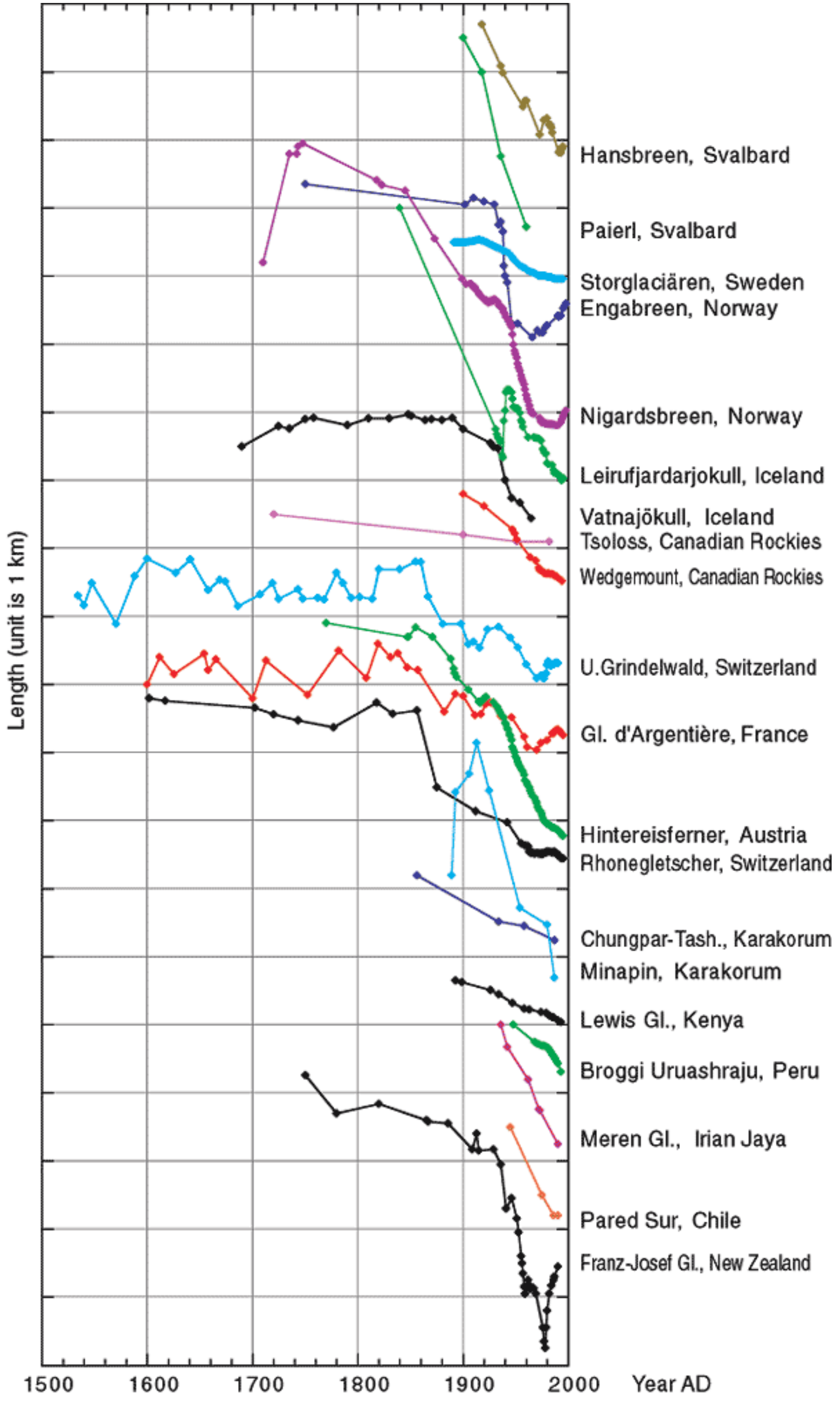
1980

Approx position 2005

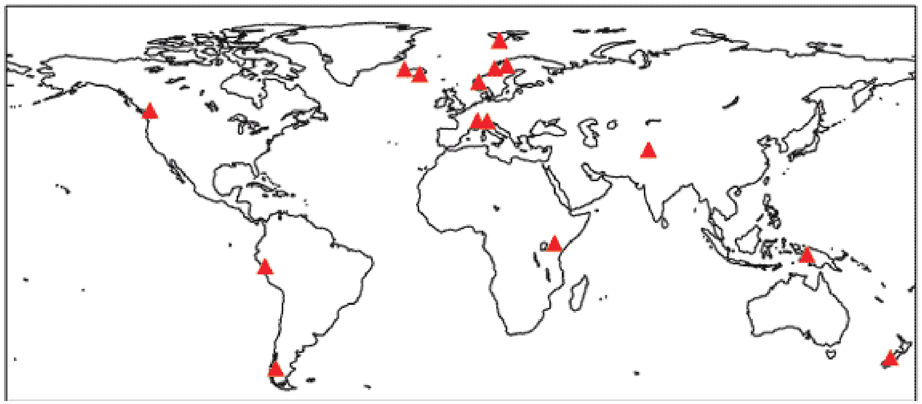
Common reference point

PENNY ICE CAP





Historical retreat of non-polar glaciers



World Glacier Monitoring Service
www.geo.unizh.ch/wgms

Glacial Retreat

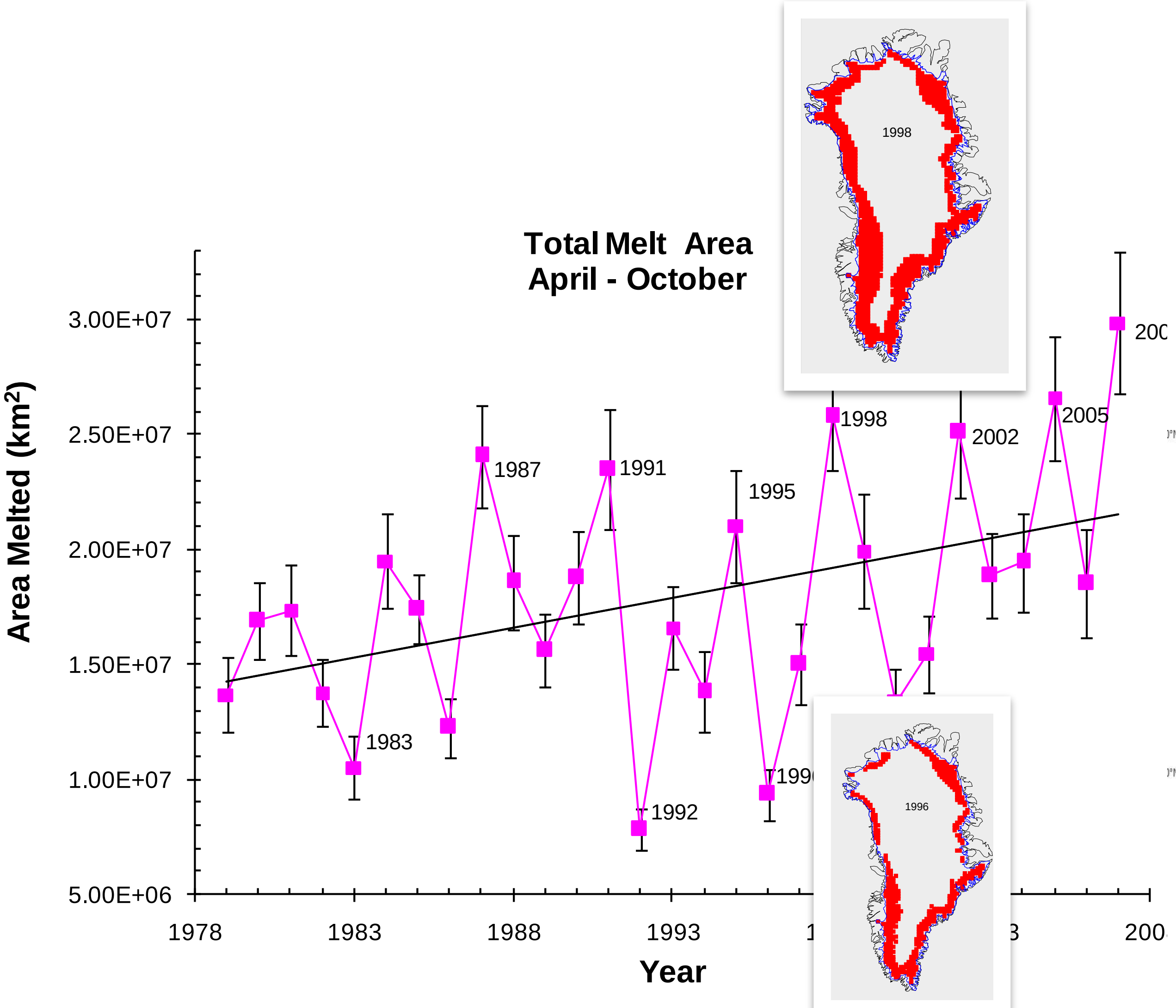
- The rapid retreat of Alaska’s glaciers represents about 50% of the estimated mass loss by glaciers through 2004 worldwide. (ACIA 2004)
- Loss of over 588 billion cubic yards between ’61 and ’98. (Climate Change 11/05)
- Alaska’s glaciers are responsible for at least 9% of the global sea level rise in the past century. (ACIA 2004)

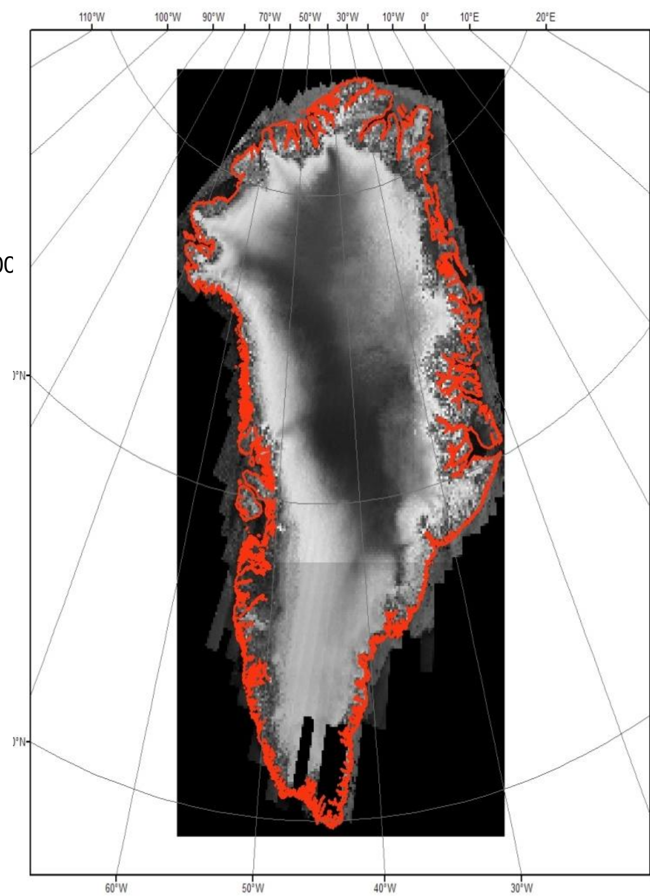
McCall Glacier

Animals at Risk

- Polar bears
- Walruses
- Ice seals
- Black guillemots
- Kittiwakes
- Salmon
- Caribou
- Arctic grayling
  - Rising temperatures
  - Shrinking habitat
  - Food harder to get
  - Expanding diseases
  - Competition

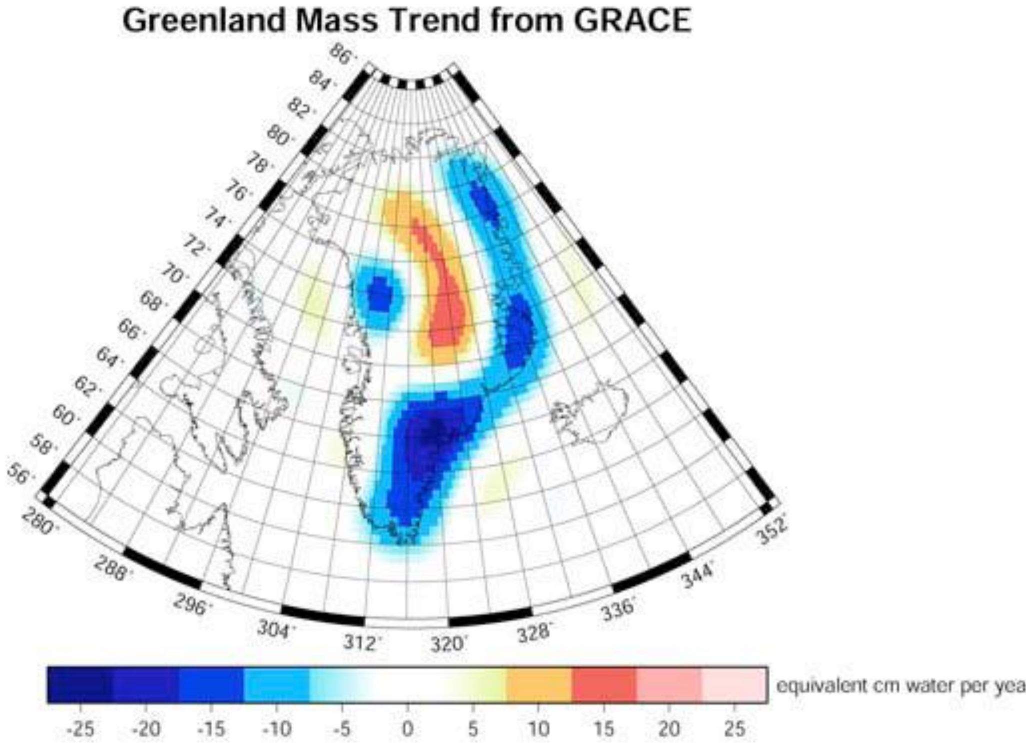
Greenland Total Melt Area 1979-2007:
2007 value exceeds last maximum by 10 %





GIIPSY

Konrad Steffen and Russell Huff, CIRES, University of Colorado at Boulder

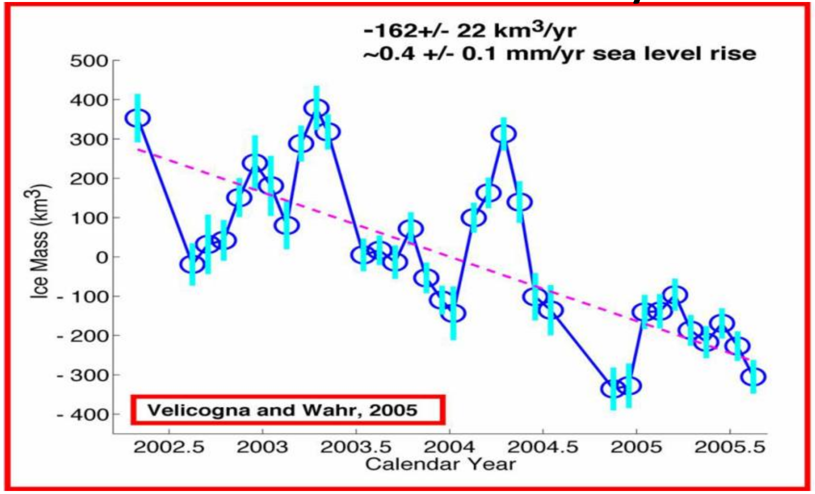


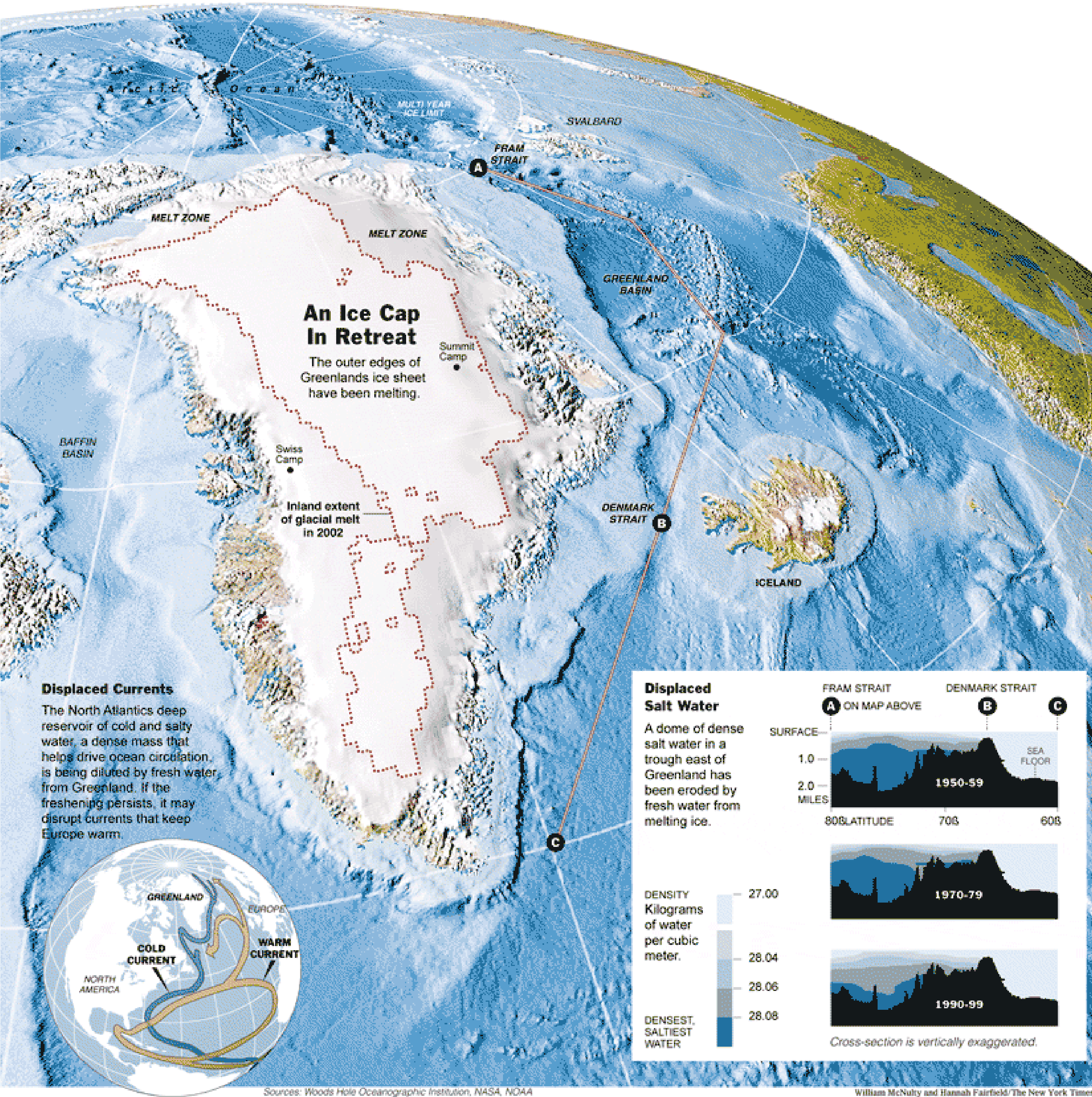
NASA satellite data has revealed regional changes in the weight of the Greenland ice sheet between 2003 and 2005. Low coastal regions (blue) lost three times as much ice per year from excess melting and icebergs than the high-elevation interior (orange/red) gained from excess snowfall Credit: Scott Luthcke, NASA Goddard

Melt descending into a moulin, a vertical shaft carrying water to ice sheet base.

Source: Roger Braithwaite, University of Manchester (UK)

Greenland Mass Loss – From Gravity Satellite

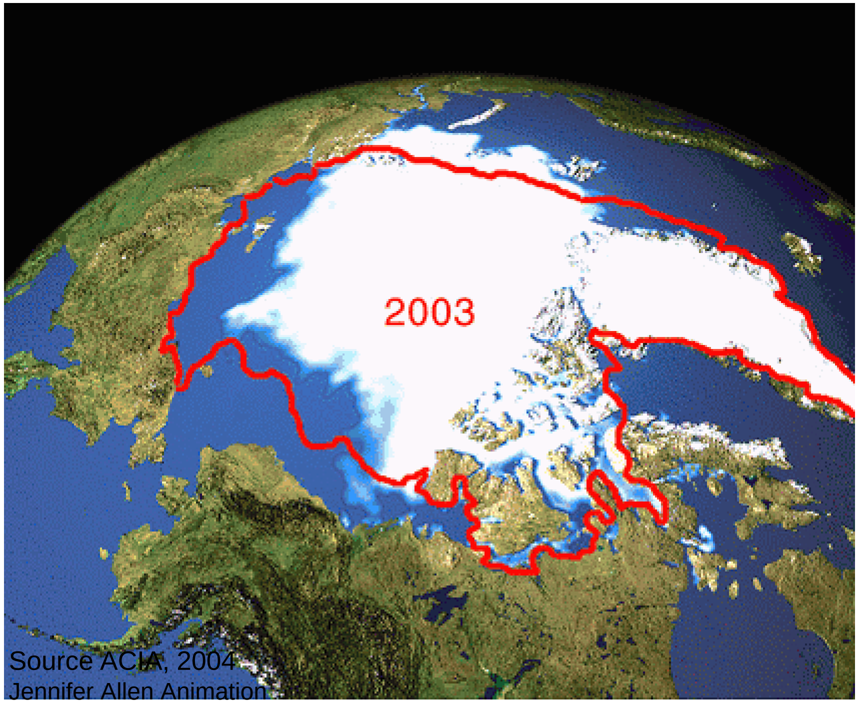


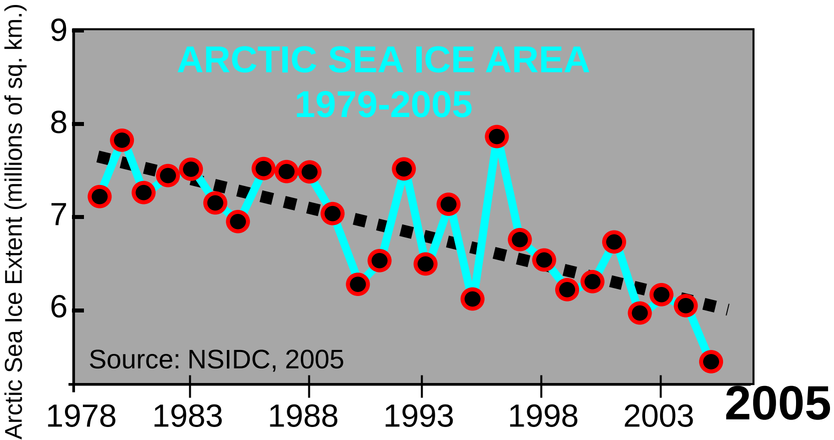


Greenland is melting

NY Times June 8, 2004

Melting Sea Ice





- An area twice the size of Texas has melted away since 1979 (over 20% decrease). (National Snow and Ice Data Center 2005)
- Ice 40% thinner. (Rothrock,D.A, et al. 1999)
- Ice only 6 – 9 feet thick at North Pole (NOAA FAQ 2007).
- Northwest passage opened Aug 21, 2007

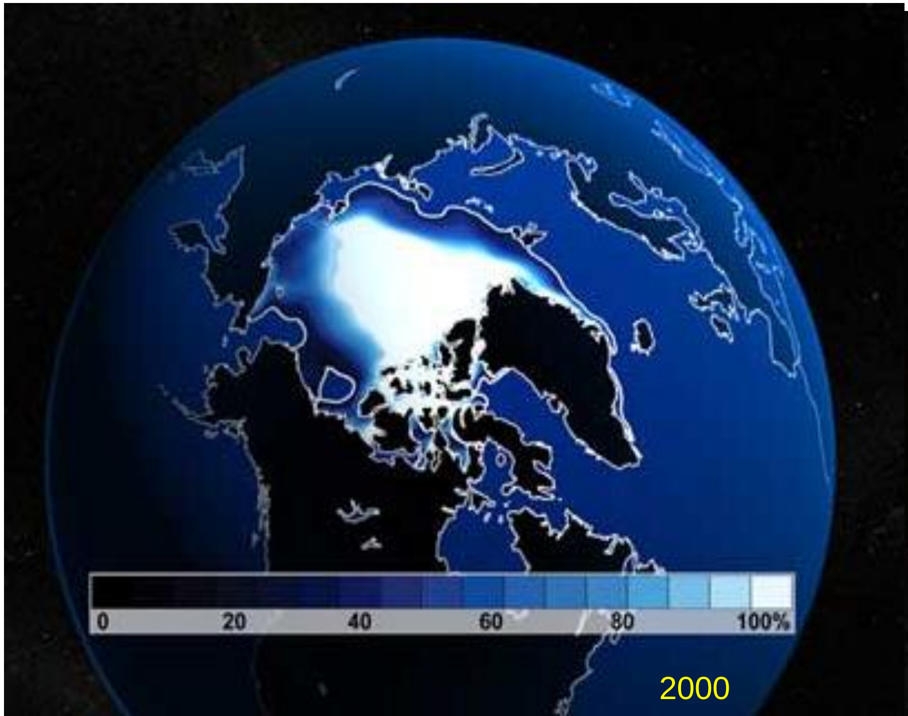
Melting Sea Ice

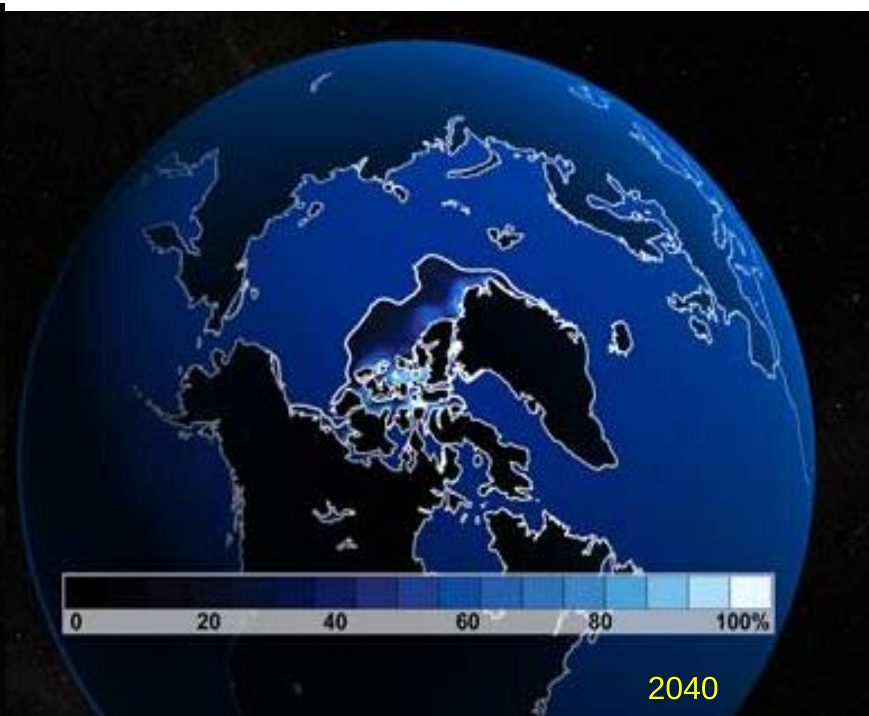
Arctic Ocean could be ice free in summer by 2040

(U.S National Center for Atmospheric Research 2006).

"Our research indicates that society can still minimize the impacts on Arctic ice."

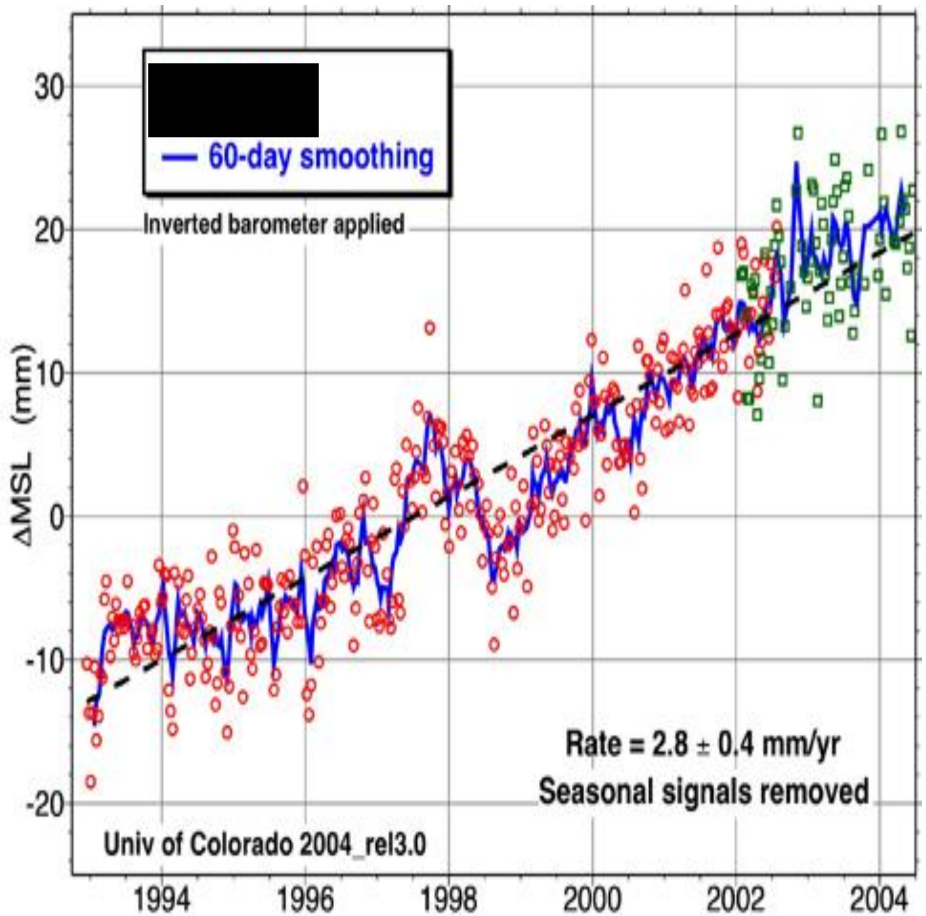
Dr. Marika Holland, National Center for Atmospheric Research





Inundation

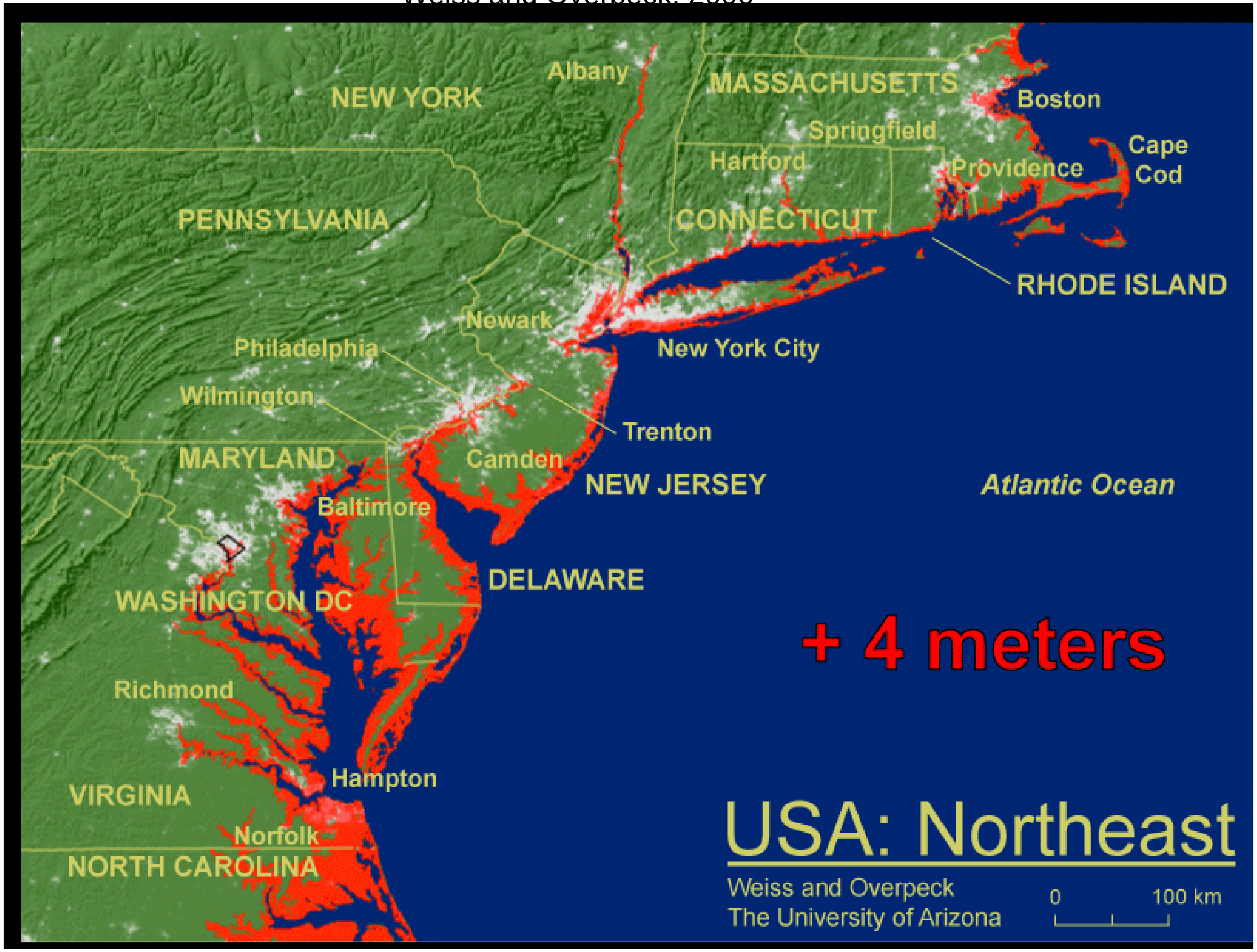
- Sea level has increased 3.1 mm/year between 1993 and 2003 (IPCC 2007).
- This is 10-20 times faster than during the last 3,000 years (ACIA 2004).
- 0.4-0.6 meters of sea level rise by 2100 if 3 times pre-industrial CO_2 or 1% increase/year (Overpeck et al. 2006).



Inundation

Inundation from Four Meter Sea Level Rise (or, 1m rise + 3m storm surge)

Weiss and Overpeck, 2006

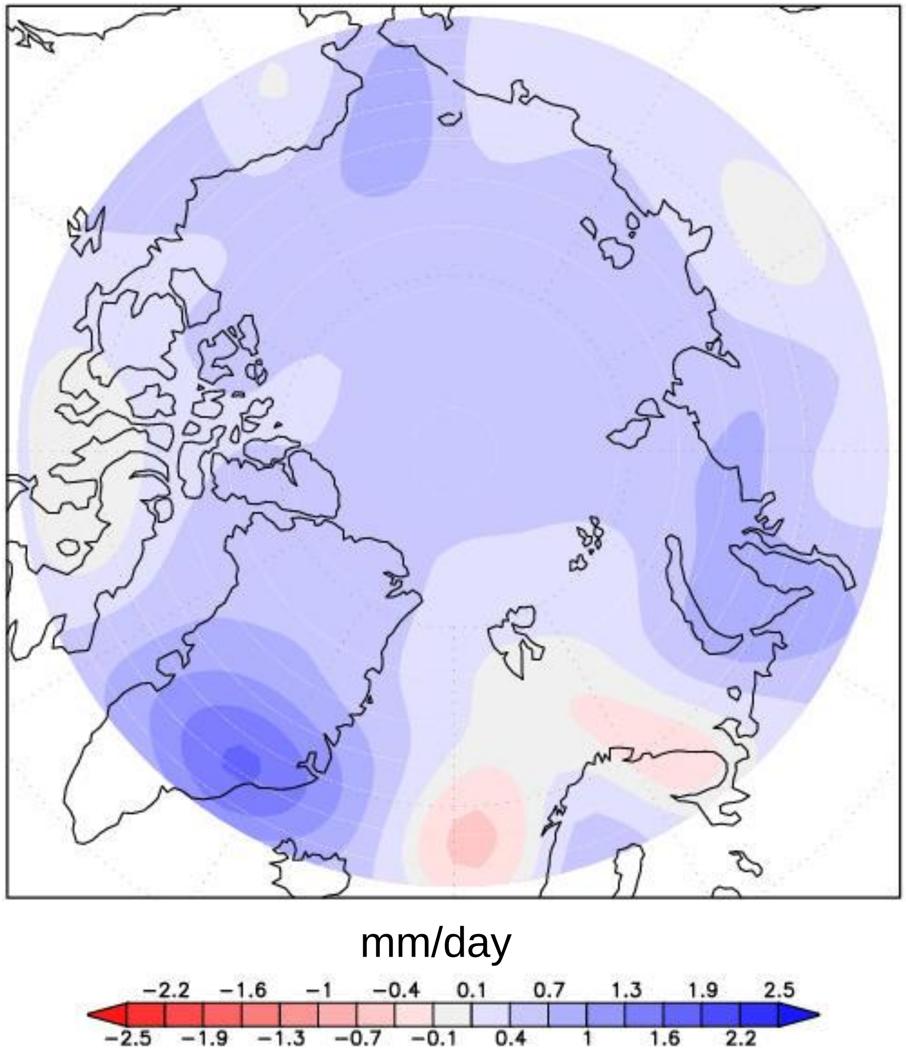


Moisture flux convergence

Horizontal distribution of vertically integrated moisture flux convergence (= P-E)

Shown here:

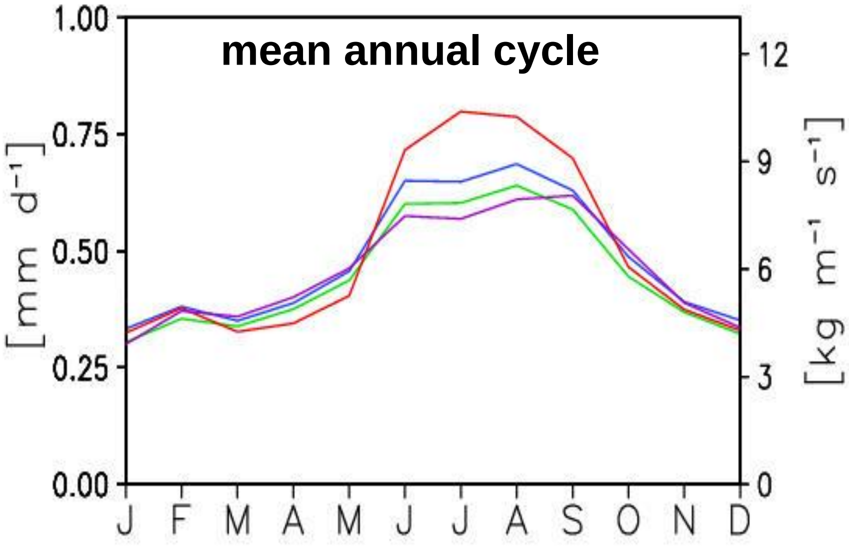
the average 1979-1993 based on mass consistent radiosonde data, smoothed to T42 (Hagenbrock 2003)

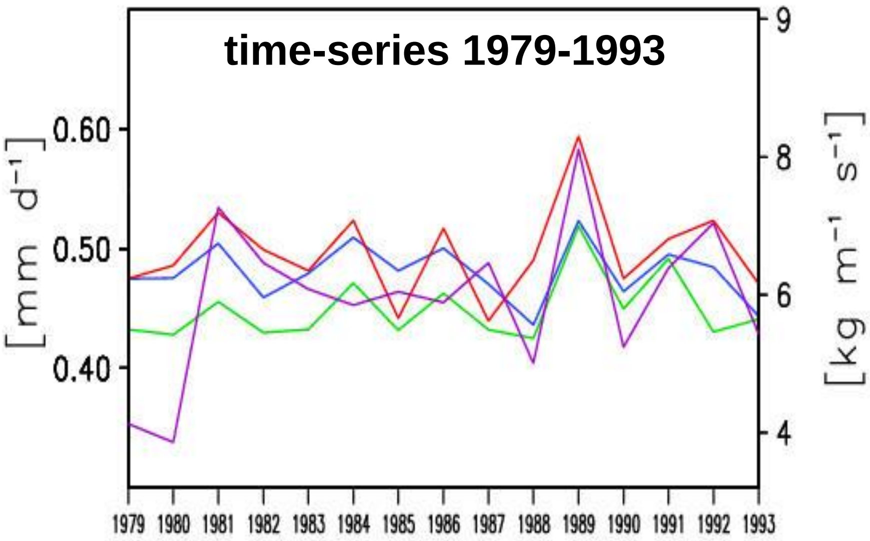


Moisture flux convergence

Vertically integrated moisture flux convergence, average 70°-90°N

Comparison of ERA-15 and radiosonde P-E average 1979-1993

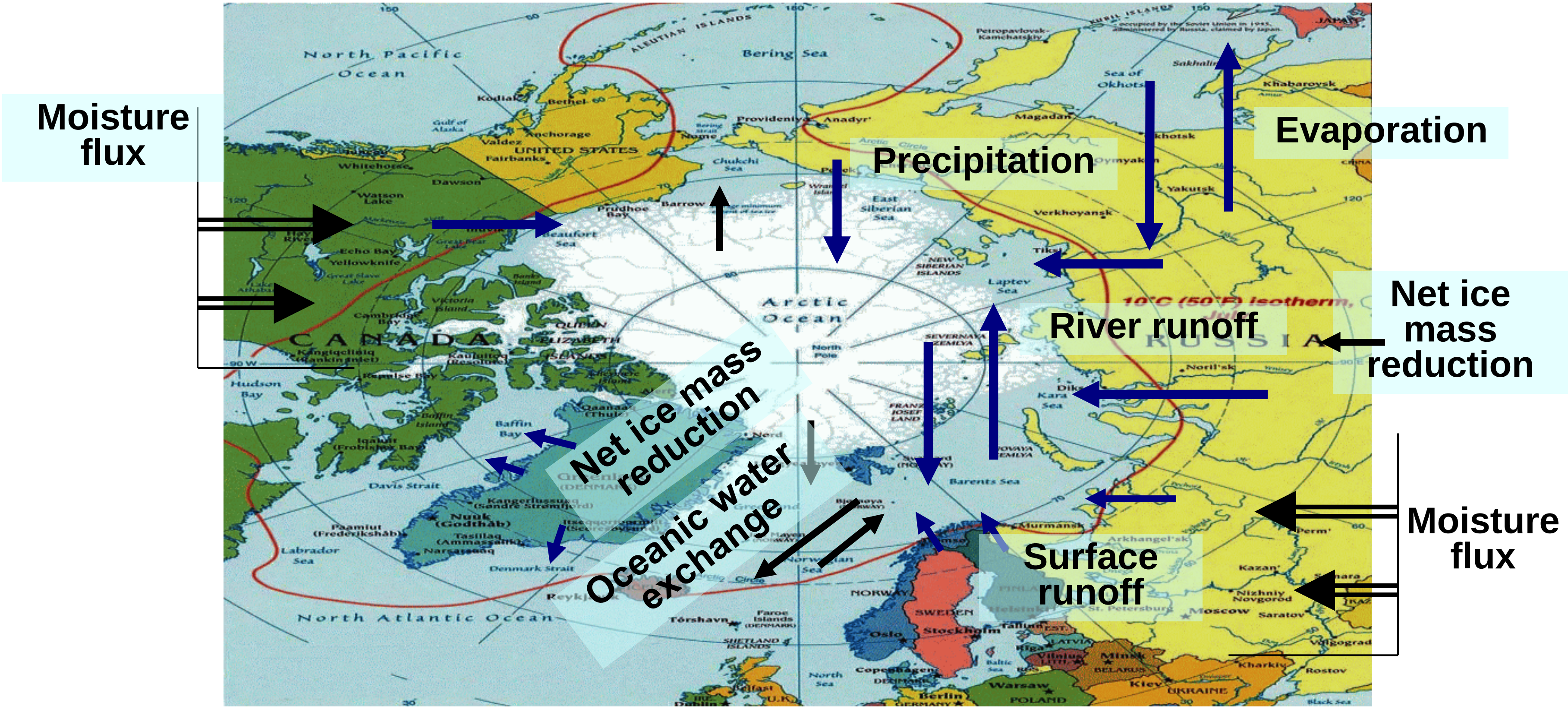




radiosonde data: average: 0.45 mm/d
ERA-15 reanalysis data: average: 0.48 mm/d
Cullather et al.: radiosonde data: average: 0.45 mm/d
Cullather et al.:ERA-15 reanalysis data: average: 0.50 mm/d

(Hagenbrock 2003, Univ. Bonn)

The Arctic Hydrological Cycle



is not a closed system but has impact from horizontal atmospheric and oceanic water mass exchange

Data and Methods

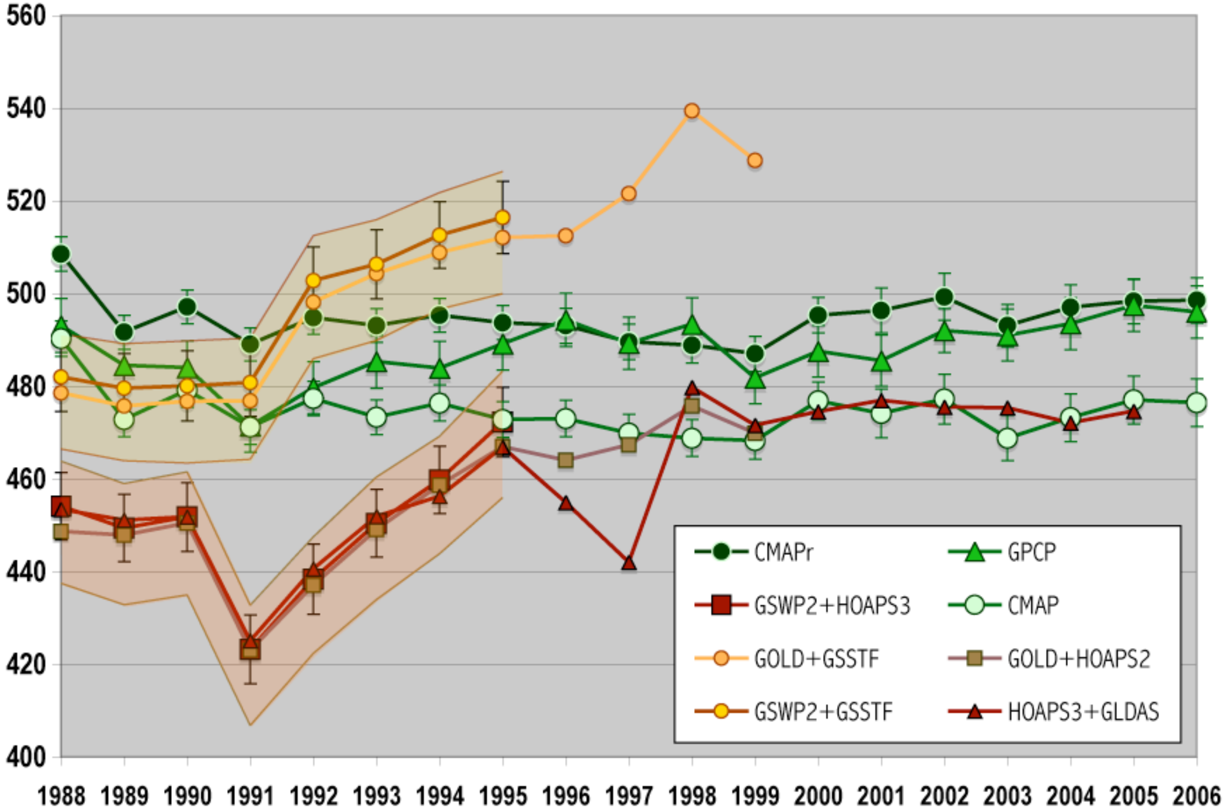
Extended Analyses (of Schlosser and Houser, J. Climate, 2007)

Fluxes	Product	Spatial	Temporal	Source & Primary Contact(s)
Precipitation	TMPA	60S ~ 60N; 180W ~ 180E (0.25°)	12Z29Jan2002 ~ present (3hr)	trmmopen.gsfc.nasa.gov (George J. Huffman)
	CMORPH	60S ~ 60N; 180W ~ 180E (0.25°)	00Z07Dec2002 ~ present (3hr)	ftp.cpc.ncep.noaa.gov (Robert Joyce & John Janowiak)
	PERSIANN	50S ~ 50N; 180W ~ 180E (0.25°)	00Z01Mar2000 ~ present (6hr)	hydis8.eng.uci.edu (Kuolin Hsu & Dan Braithwaite)
Evaporation	GLDAS (Land)	60S ~90N; 180W ~ 180E (1°)	Jan1979 ~ Aug2006 (Monthly)	hsbserv.gsfc.nasa.gov (Matthew Rodell)
	HOAPS (Ocean)	80S ~ 80N; 180W ~ 180E (1°)	00Z01Jan1987 ~ 12Z31Dec2005 (12hr)	www.hoaps.zmaw.de (Axel Andersson)
Storage	AIRS-AMSRE (Atmosphere)	90S ~ 90N; 180W ~ 180E (1°)	00Z01Jan2005 ~ 21Z31Dec2005 (3hr)	JPL (Eric Fetzer and Van Dang)
	GRACE (Terrestrial)	90S ~ 90N; 180W ~ 180E (1°)	CSR: Aug2002 ~ Dec2006 GFZ&JPL: Feb 2003 ~ Nov 2006 (Monthly)	podaac.jpl.nasa.gov (Don Chambers and Jay Famiglietti)
Moisture Transport	MOIS_TRANS	30S-30N; 180W-180E (0.5°)	07Jul1999 ~ 31Dec2005 (daily)	airsea.jpl.nasa.gov (Timothy Liu & Xiaosu Xie)

Atmospheric Budget: $dQ/dt = E - P - div(Q_t)$

Terrestrial Budget: $dS/dt = P - E - R$

Global Results: 1988-2001

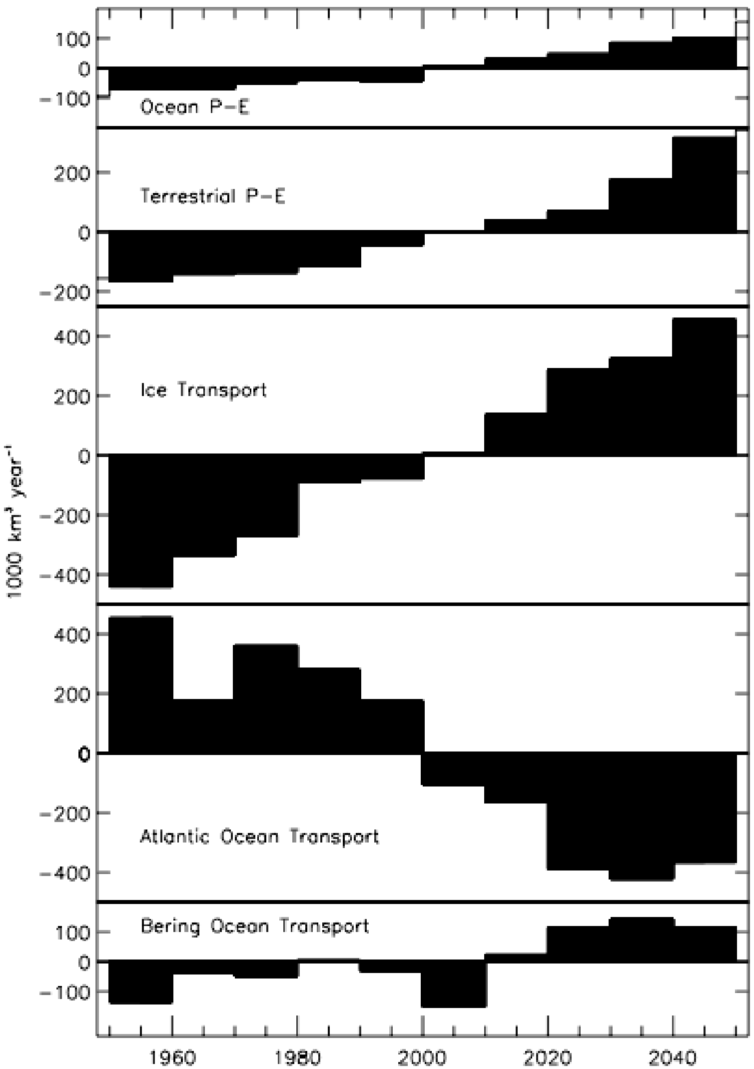


	GPCP	CMAP	CMAPr	HOAPS & GOLD
Land	1.07±0.02	9.98±0.01	1.00±0.01	0.684
Ocean	3.79±0.06	3.74±0.04	3.94±0.04	3.95
Global	4.86±0.06	4.75±0.04	4.94±0.04	4.63

Table 1. Global annual mean results of water budget terms for the period 1988-2001. Values are given in units of 10^{17} kg/yr.

- HOAPS (still) shows trend and Pinatubo plunge.
- GPCP/CMAP(r): The good, the bad, and the "split"
- Latter half of period, fluxes converging, really?
- Trend detection - need long monotic trend to verify GCMs (for low-risk detection).

Evidence for an accelerating FW cycle



Positive means net flux into Arctic

Multi-model mean changes in Arctic Ocean FW Budgets 1950-2050

- Increasing net precipitation over land and ocean
- Increasing ice melt, resulting in reduced ice transport
- Increasing liquid FW transport to the Atlantic ocean
- Small increase in Bering Strait FW inflow

Holland et al., 2007

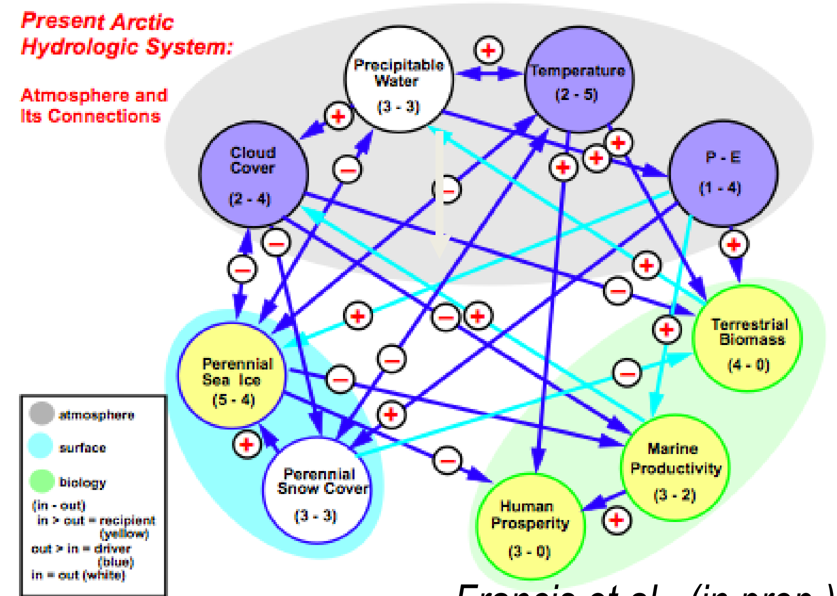
CHANGES AND ATTRIBUTION

White et al. JGR, Biogeosciences (submitted)

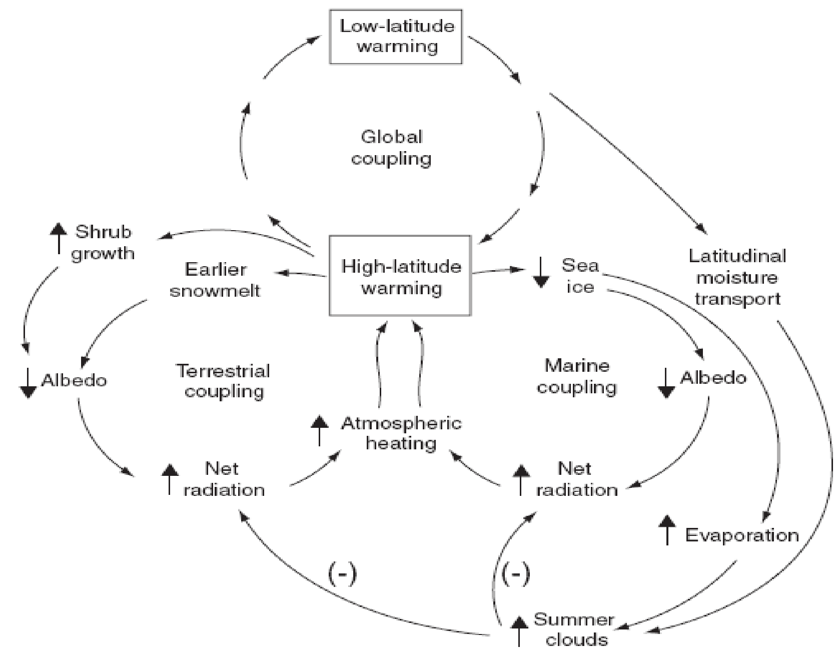
Changes in Key Stocks and Fluxes
Over "Period of Record"

VARIABLE	TREND	CONFIDENCE
Atmospheric Moisture Transport	Increasing	Very Good
Atmospheric Storage	Increasing	Very Good
Precipitation	Increasing	Very Good
River Discharge – Eurasian River Discharge – N. American	Increasing No Trend	Very Good Good
Lakes / Wetland	?	?
Reservoirs	Increasing	Excellent
Groundwater	?	?
Permafrost – Active Layer Thickness – Eurasia Active Layer Thickness – N. America Permafrost – Storage	 Increasing No Trend ?	 Good Good ?
Sea Ice – Area Sea Ice – Volume Sea Ice – First Year	Decreasing Decreasing Decreasing	Excellent Good Excellent
North Atlantic / Nordic Sea	Increasing	Excellent
Fram Strait Outflow – Liquid Fram Strait Outflow – Ice	? Increasing	? Very Good?
Pacific Inflow	Increasing	Very Good
Arctic Ocean	?	?

Feedbacks & implications on major subsystems



Francis et al., (in prep.)



Arctic Land Water Cycle Change

- Ground temperatures are rising and permafrost is thawing.
- Sea ice extent, thickness and volume are decreasing.
- Glaciers and ice sheets are retreating, thinning and losing volume.
- Duration of snow cover is decreasing due to earlier melt in spring.
- Differential warming
- Shift in hydrograph earlier in year
- More summer convective precipitation
- Increase in river discharge

Strategic issues (from the standpoint of Arctic Land Hydrology)

• What processes are most critical, and how can the observational base best be improved?

• ***Rivers*** – major rivers are reasonably well gauged (notwithstanding budget pressures, and complications of estimating discharge during ice breakup, etc) – however “interior” gauge network is sparse, and under continuing pressure, generally number of Arctic gauges has declined over land ~20 years. Possible role of swath altimetry (complications include ice cover, overpass interval)

• ***Snow on ground*** – some in situ measurements, but vast area – remote sensing offers promise, and some success already with passive microwave sensors (most algorithms use 19/37 GHz channels). Complications include mixed pixels (especially forest), and topography, among others.

• ***Evapotranspiration*** – usually by difference, possibility for indirect inference and measurement of key variables (Ts, vegetation indicators) via remote sensing

• ***Precipitation*** – role of GPM? Sampling issues? Strategies for data assimilation?

• Need to move towards ***advanced process models***, assimilation methods, and validation.

• Need to move ***toward integrated science assessments*** (i.e. putting the water cycle pieces together), and interdisciplinary big-picture teamwork.