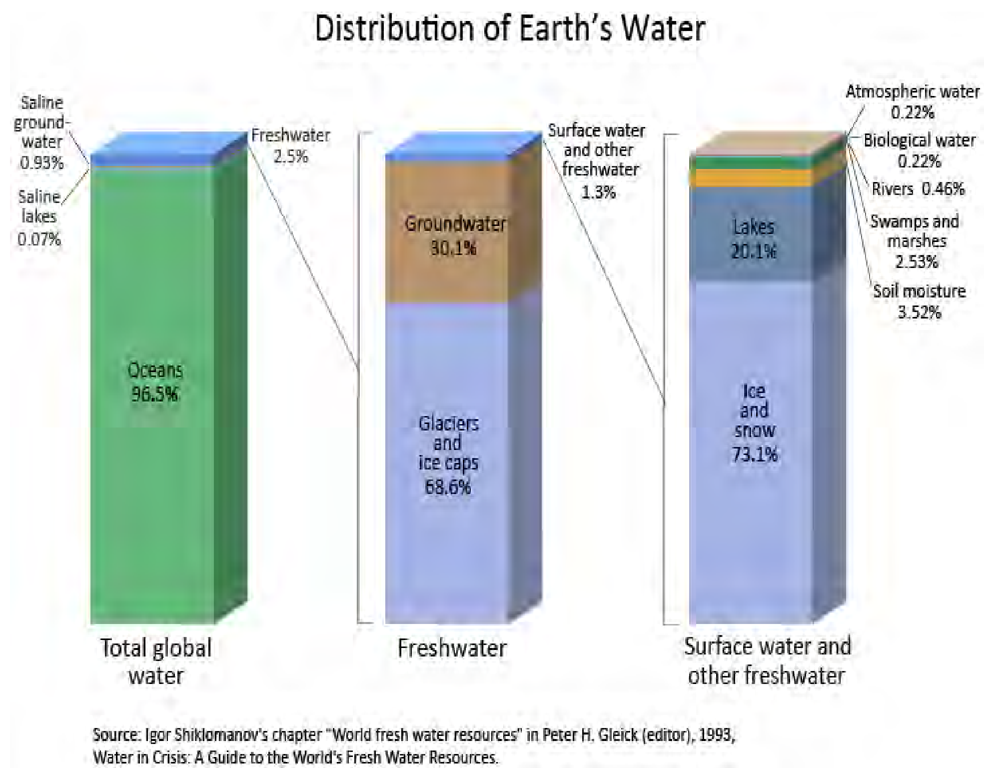
- The world's two main reservoirs of fresh water are the great polar ice caps, and the ground.
- If all of the ice in the ice caps and other glaciers melted, it would raise the sea level by about 80 m.



A run through

The Polar Water Cycle

Input - Output = Storage Change

$P + Gin - (Q + ET + Gout) = \Delta S$

$Rn - G = Le + H$

Observe and predict:

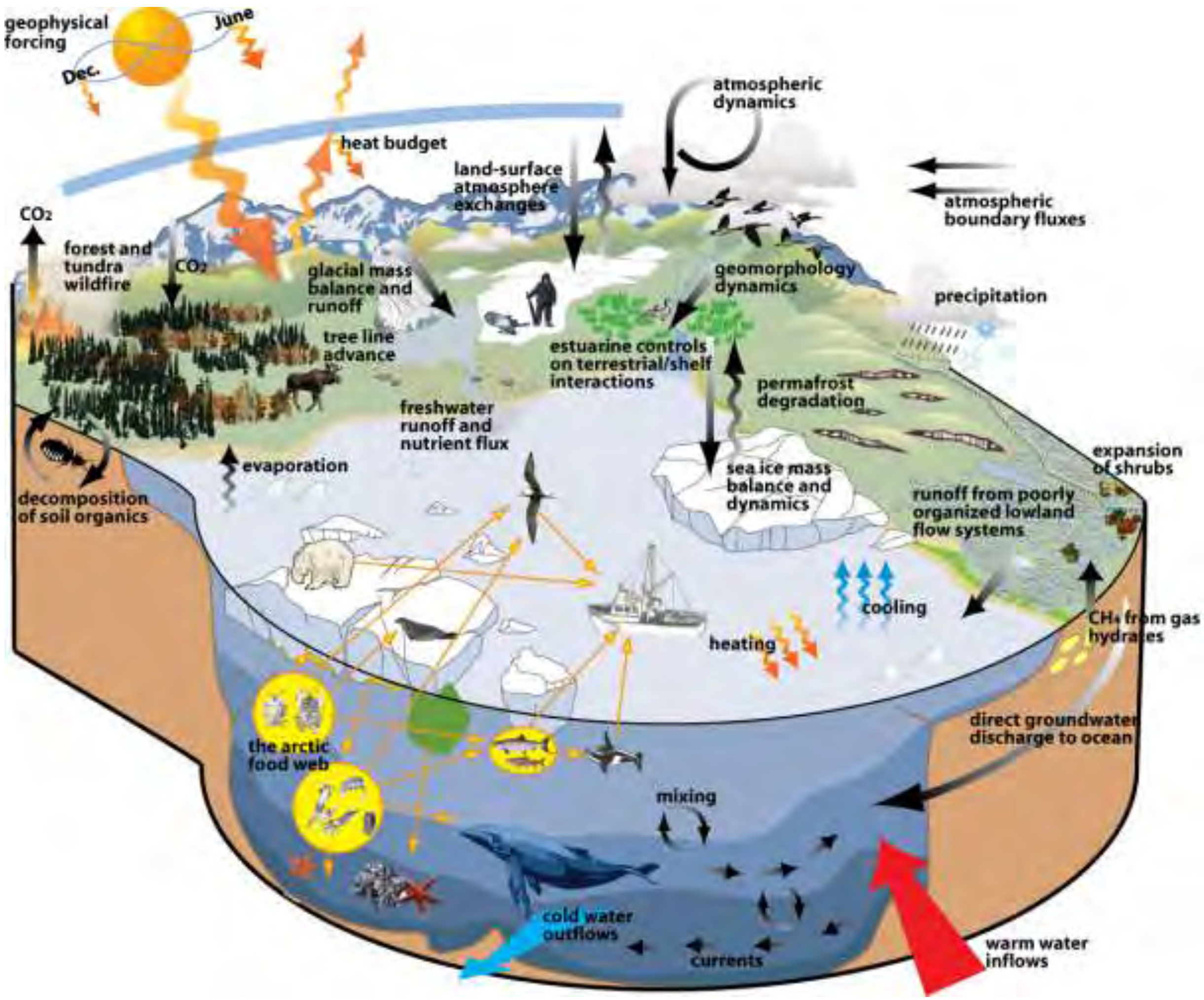
- Precipitation (solid, liquid)
- River runoff (discharge)
- Land Ice
- Snow Cover

Boundary information:

- Temperature & Permafrost
- Salinity
- Vegetation

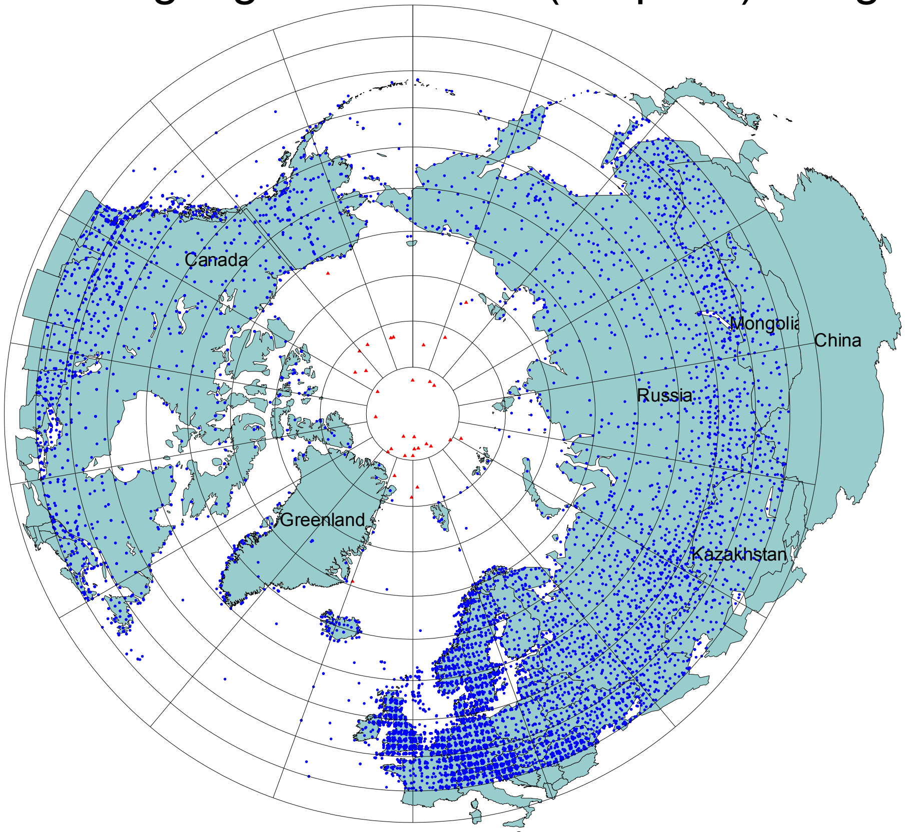
Water Cycle:

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

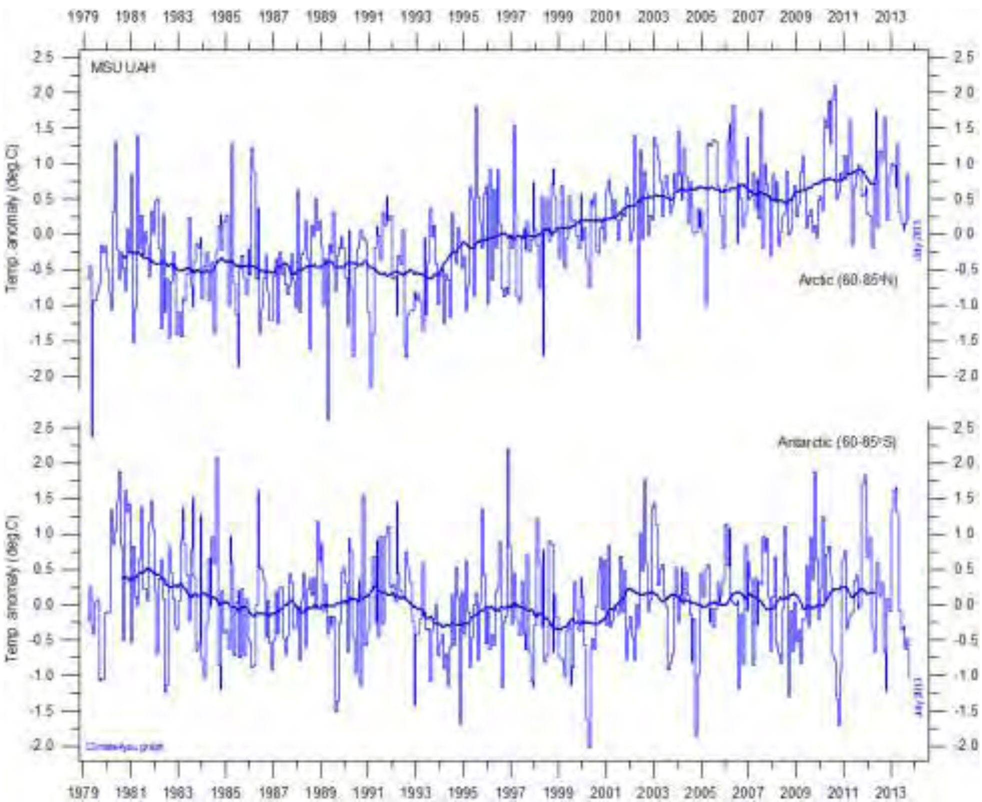


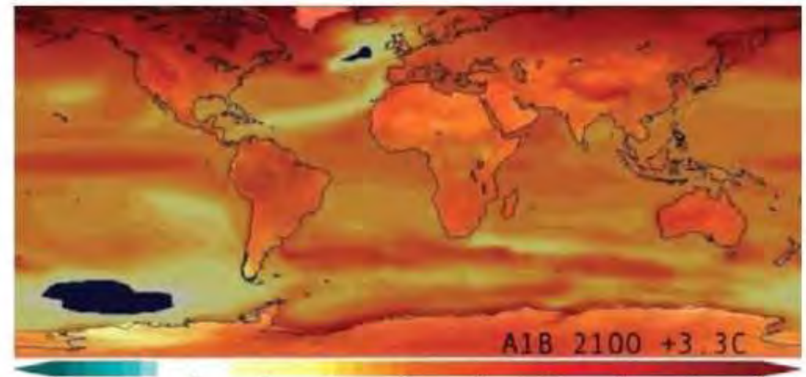
Arctic Land Water Cycle: Measurement difficulties

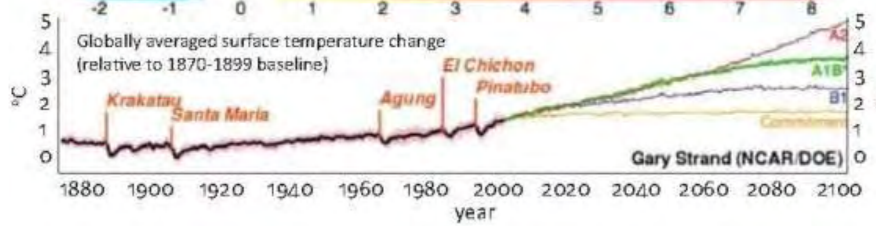
- •Most of the region is remote, access difficult (e.g., expense of running USGS stream gauges in Alaska -- ~ 5-10 x relative to lower 48).
- •Station densities (especially precipitation) tend to be where the population is (hence major gaps in Arctic interior)
- •Extreme environment, hard on instrumentation
- •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

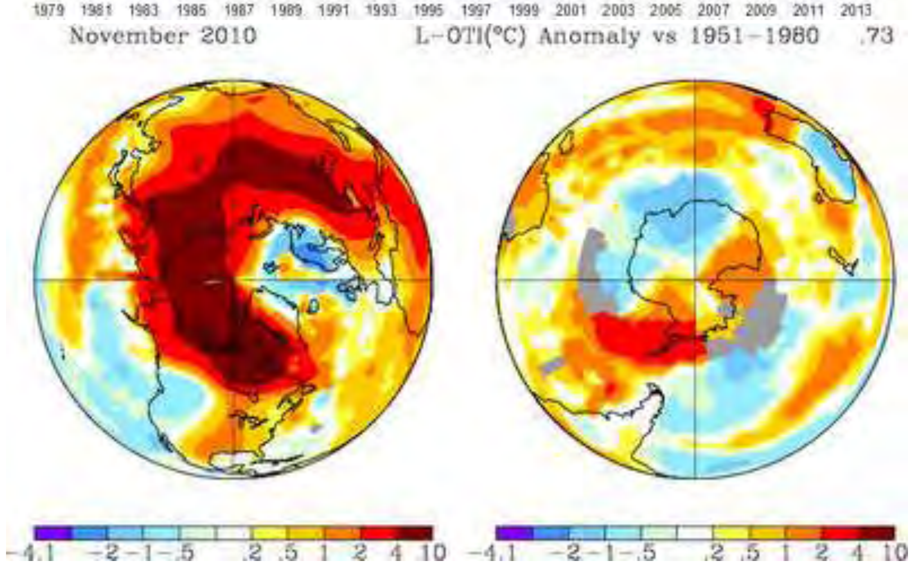


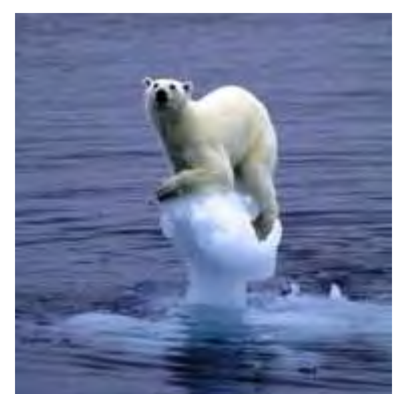
TEMPERATURE











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

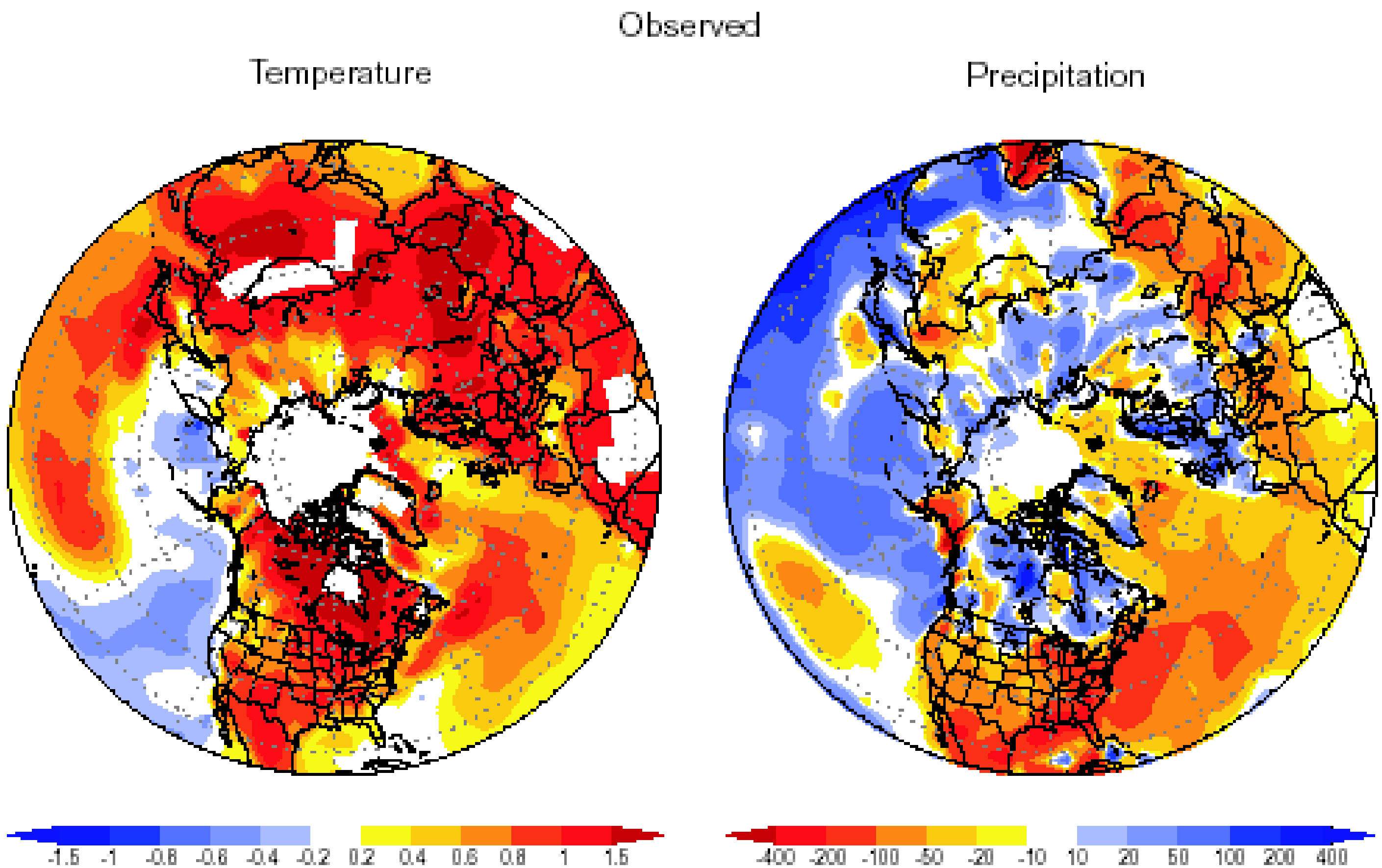
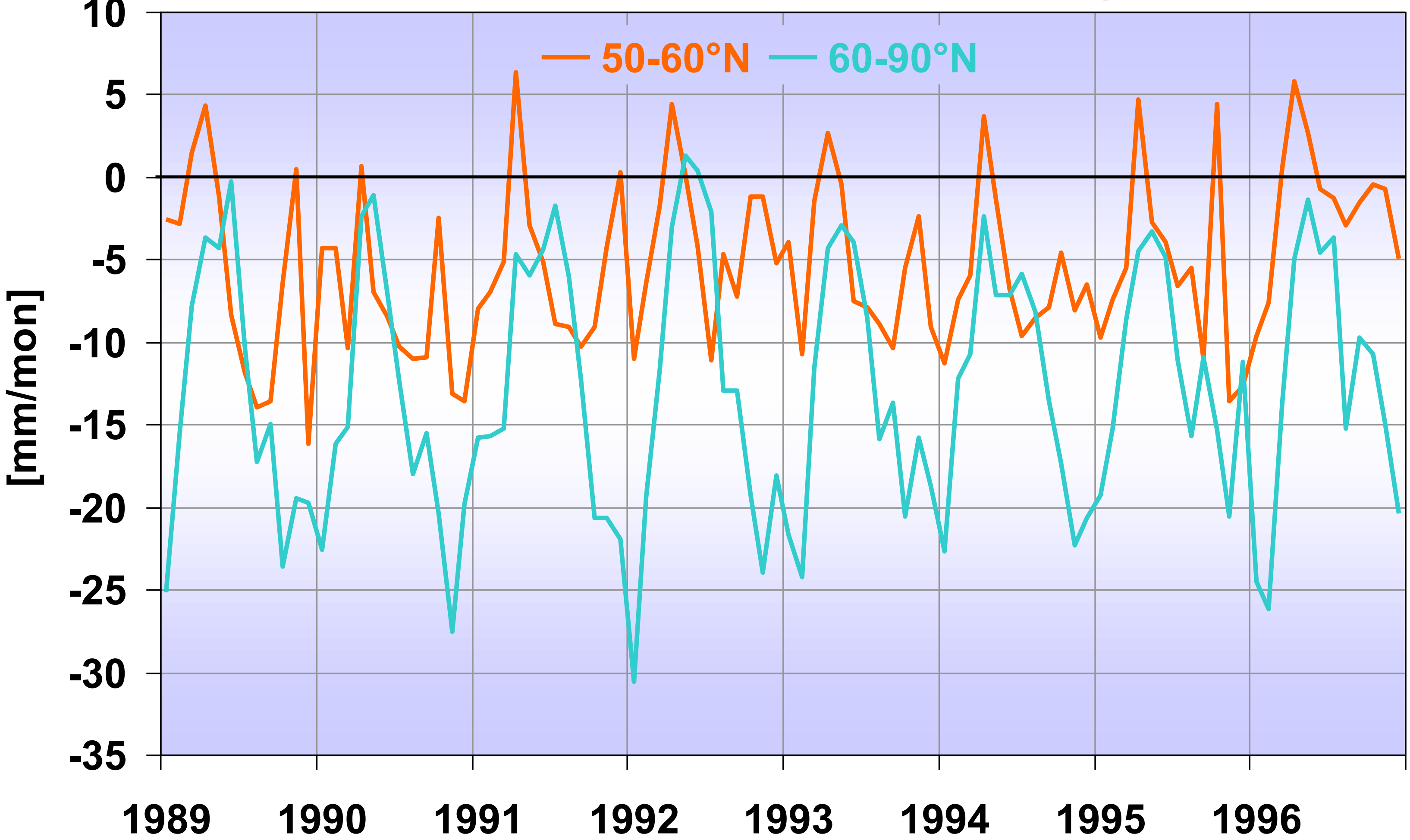
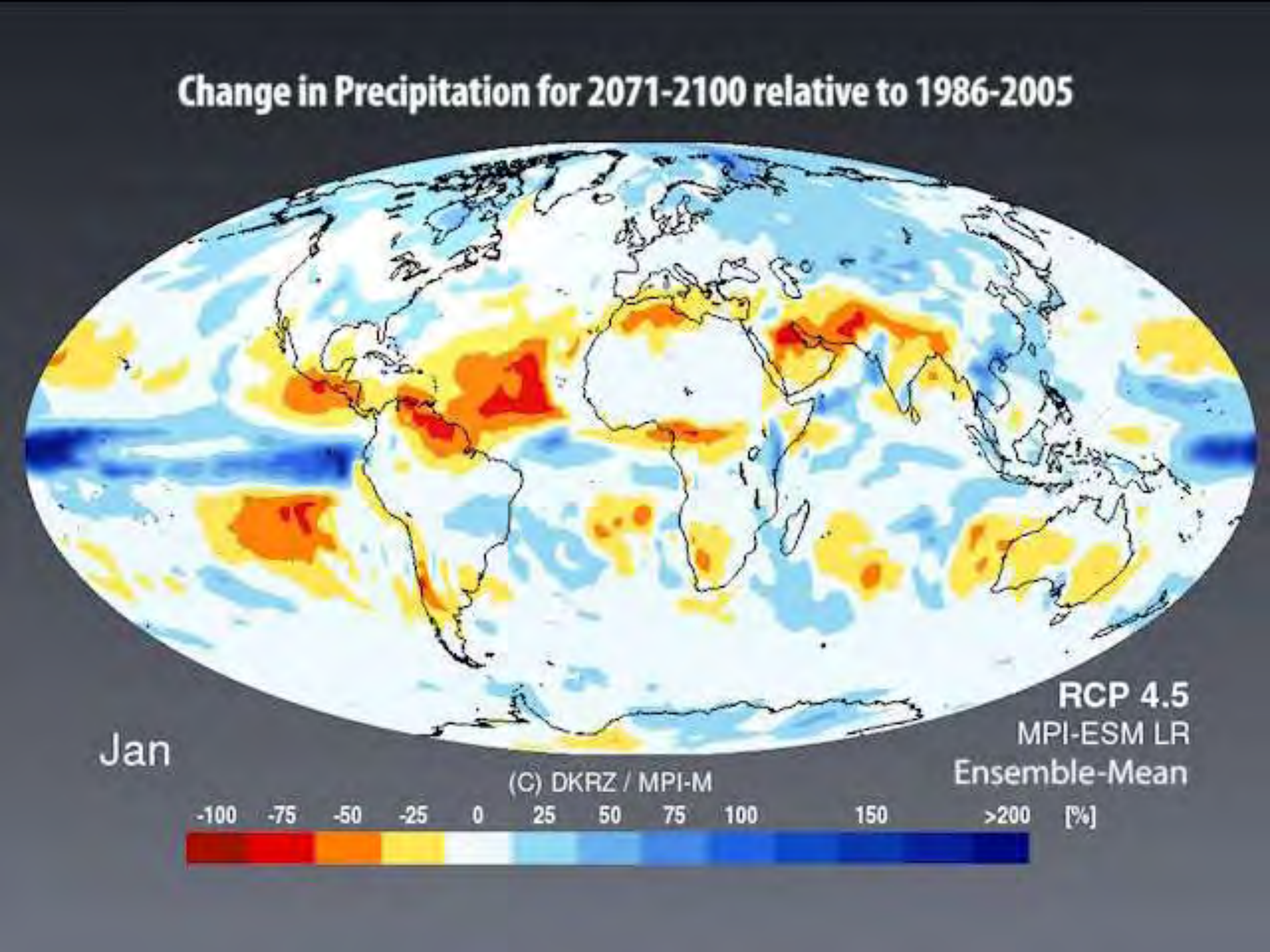


Fig. 1. Observed, annually averaged surface temperature (**left**) and precipitation (**right**) anomalies during the 4-year period June 1998–May 2002. Temperature departures are degrees Celsius

The Arctic Hydrological Cycle
of NWPM Reanalysis ERA-40

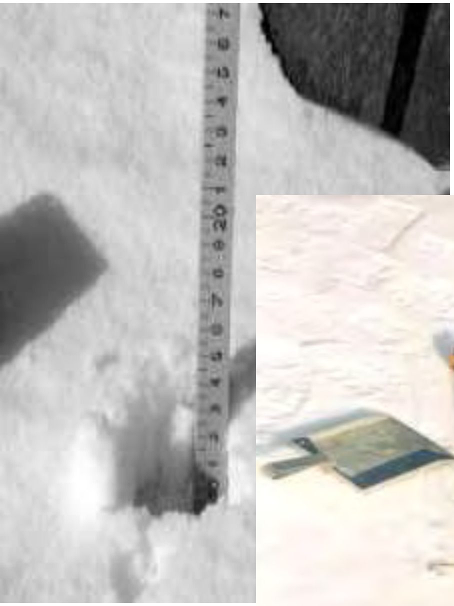
Differences of zonal area-mean precipitation for ERA-40 minus GPCP V2 Sat-Gauge

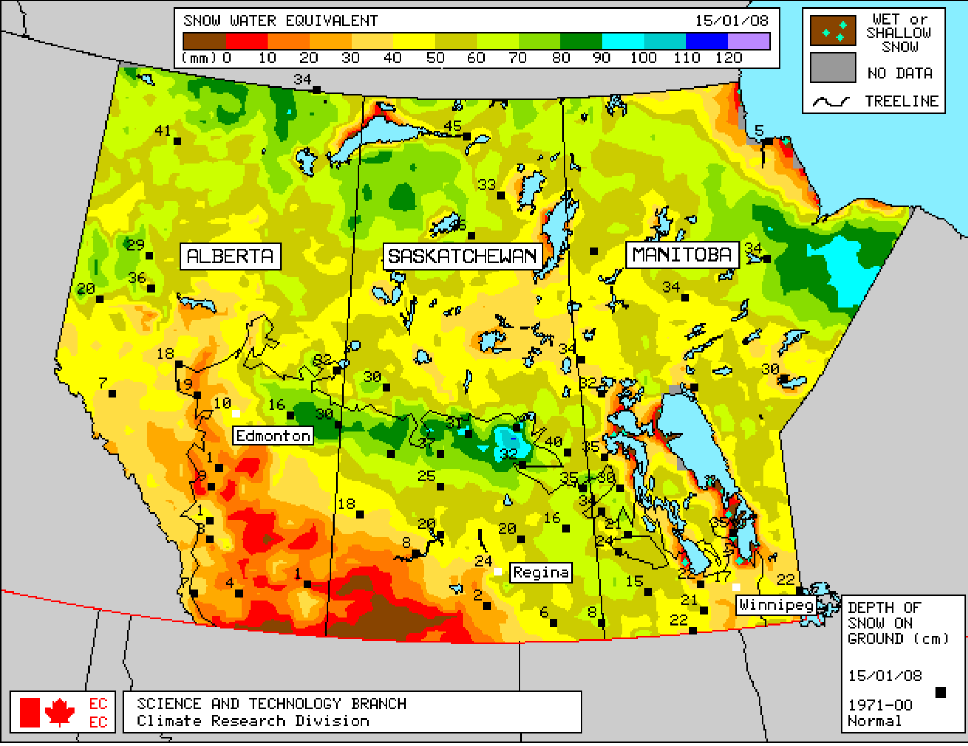



Change in Precipitation for 2071-2100 relative to 1986-2005
RCP 4.5
MPI-ESM LR
Ensemble-Mean
Jan
(C) DKRZ / MPI-M
-100 -75 -50 -25 0 25 50 75 100 150 >200 [%]

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





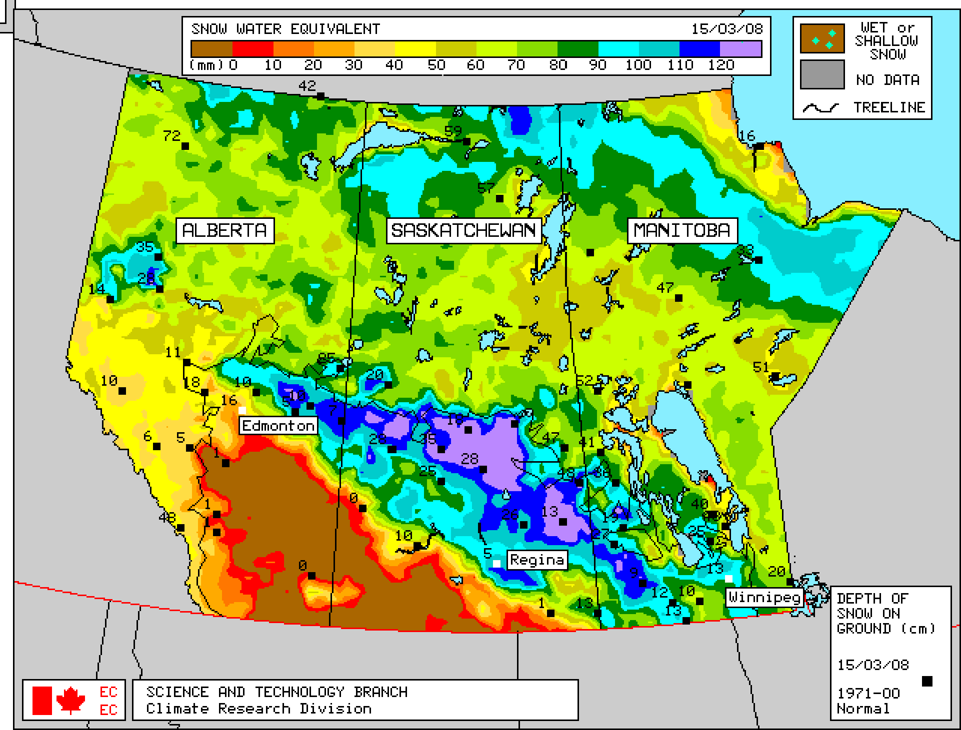
Example:

Snow Water Equivalent

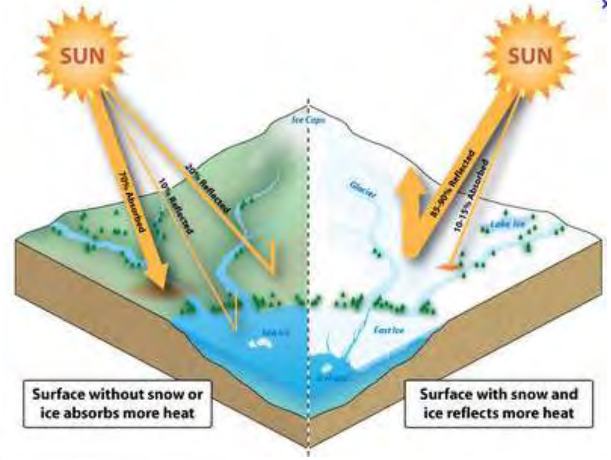
SWE derived from AMSR-E for Western Canada

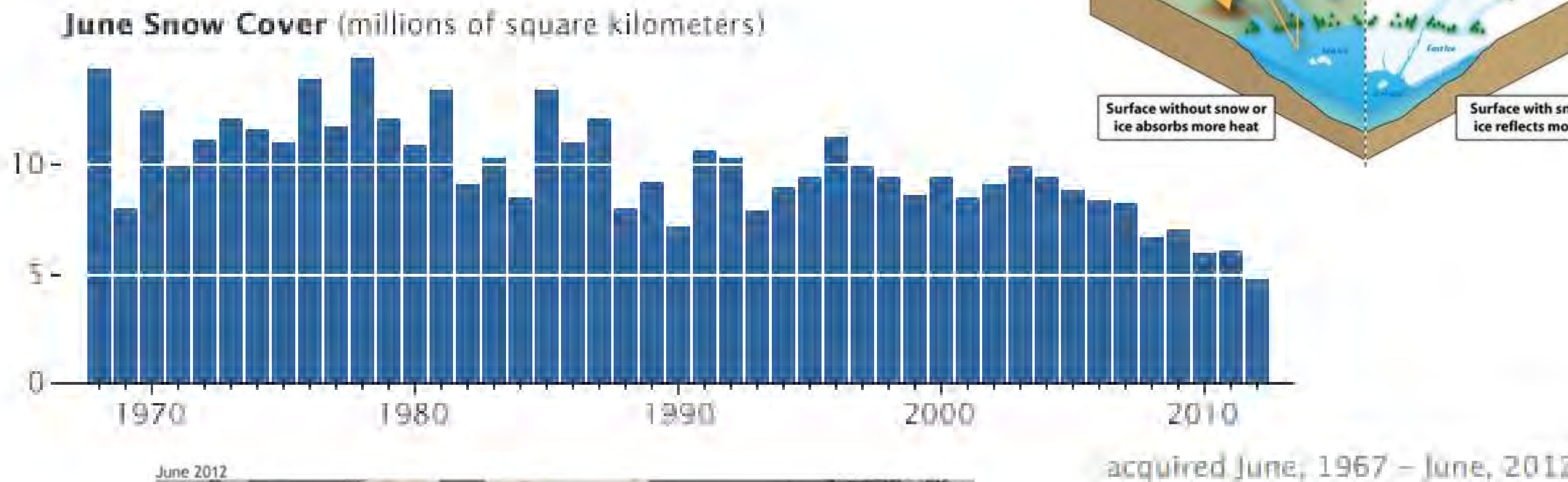
Issues for GCW?

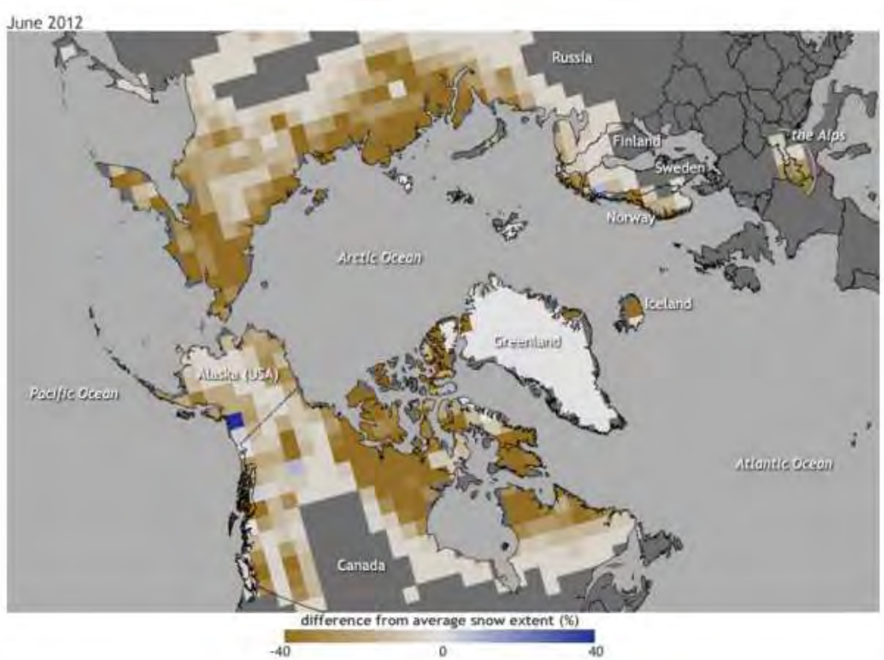
- evaluation of the product
- how consistent is the derived SWE
- evaluation of the algorithms
- transferability of algorithms
- usefulness of the product
- sustainability of product development and production
- when will this product be ready to transfer from research to operations



How is Arctic snow cover changing?







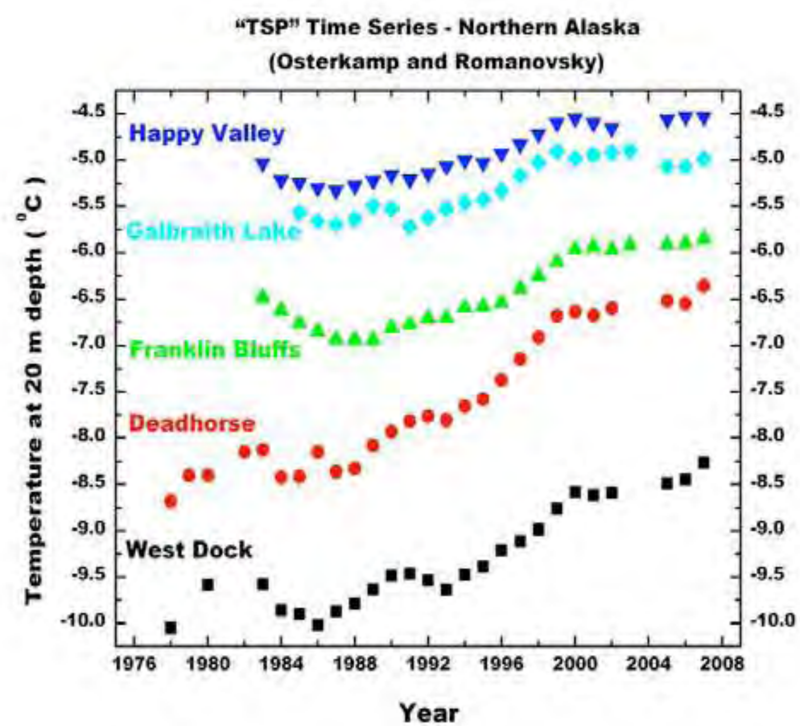
Permafrost

- 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.

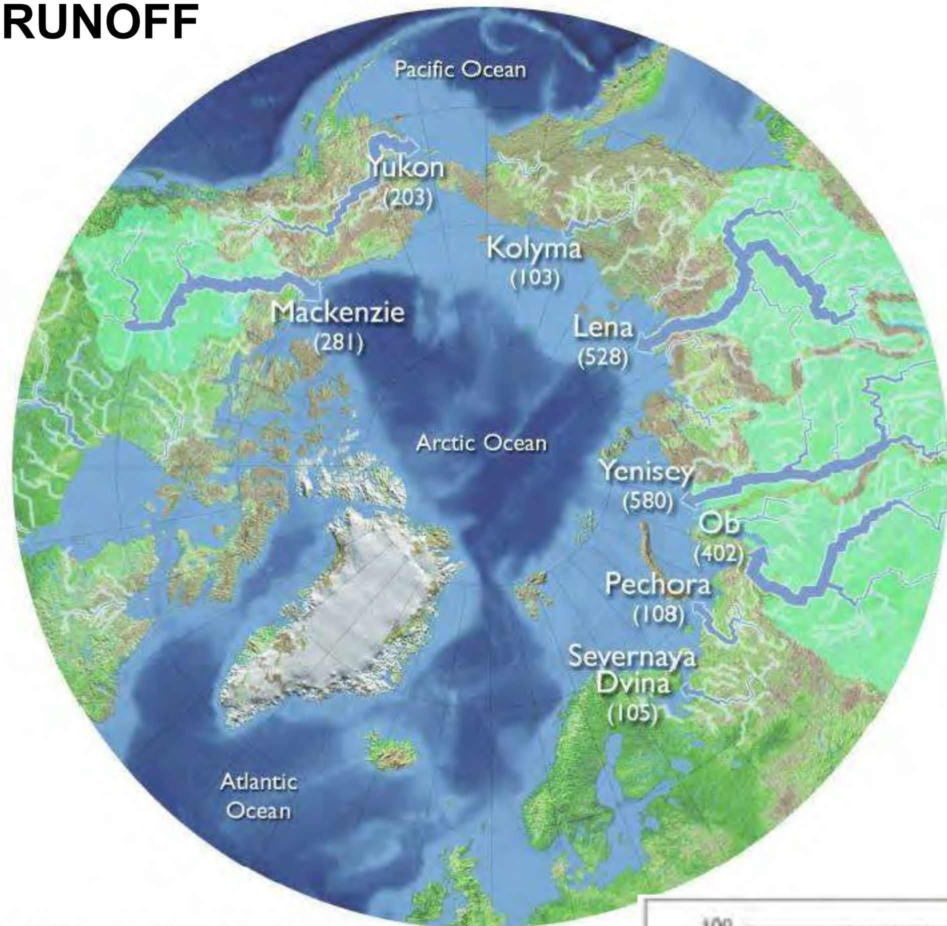
- Biggest concern are soils with the potential for instability upon thaw (thaw settlement, creep or slope failure). Such instabilities may have implications for the landscape, ecosystems, and infrastructure. (GSC 2002)

- Thawing of permafrost is likely to release CO_2 and CH_4 that have been trapped in the frozen soil, further contributing to global warming.



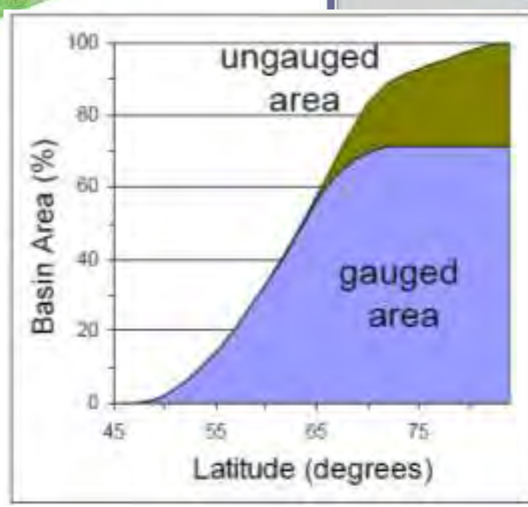
Changes since 1978 in permafrost temperatures at 20 m depth (updated from Osterkamp 2003). Northern Alaska. ARC 2008.

RUNOFF



Pacific Ocean
Yukon
(203)
Kolyma
(103)
Mackenzie
(281)
Lena
(528)
Arctic Ocean
Yenisey
(580)
Ob
(402)
Pechora
(108)
Severnaya
Dvina
(105)
Atlantic
Ocean

Mackenzie
Lena
Ob
Yenesei



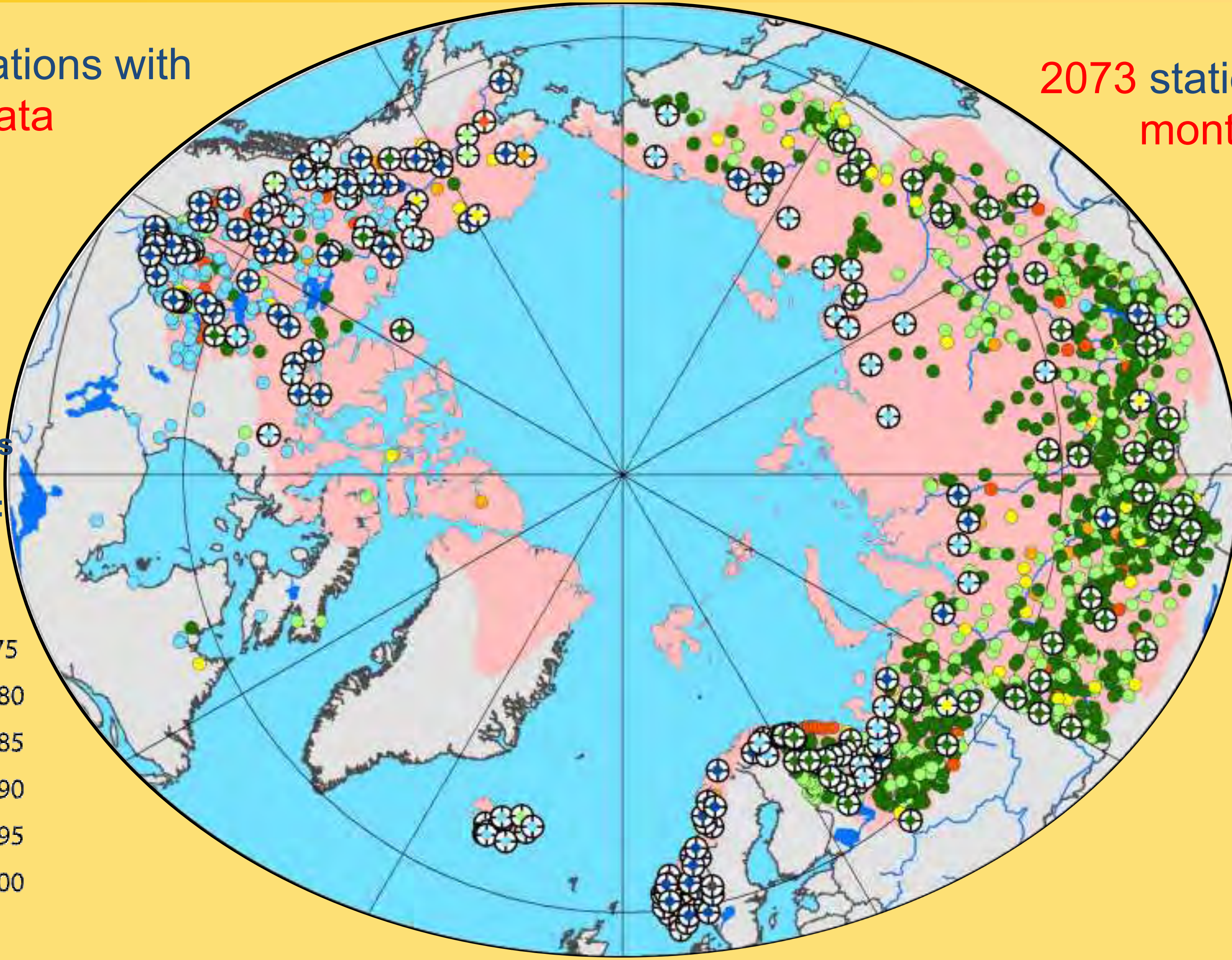
ungauged
area
gauged
area
Basin Area (%)
100
80
60
40
20
0
45
55
65
75
Latitude (degrees)

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

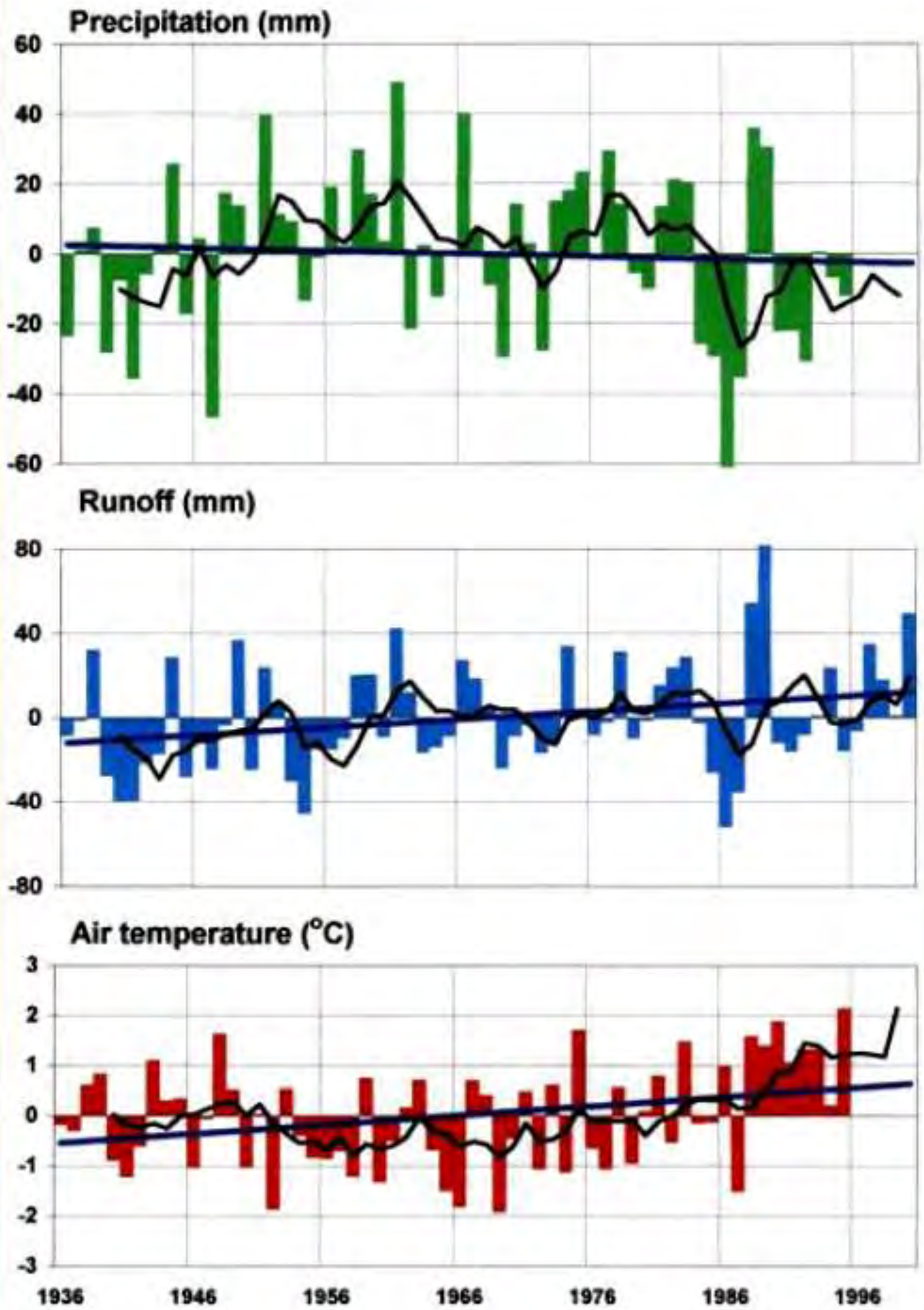
- < 1970
- 1971- 1975
- 1976 - 1980
- 1981 - 1985
- 1986 - 1990
- 1991 - 1995
- 1996 - 2000
- > 2000

time series end for monthly data:

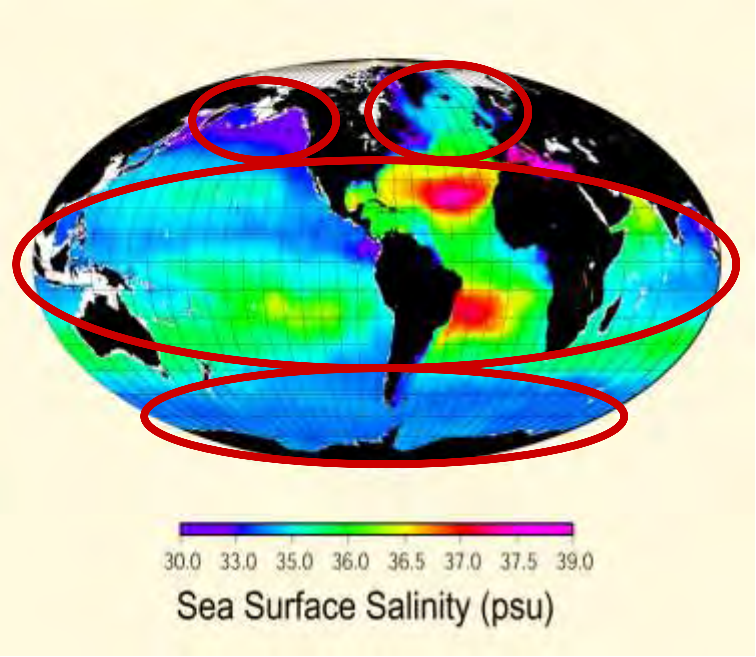
monthly data

- < 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



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



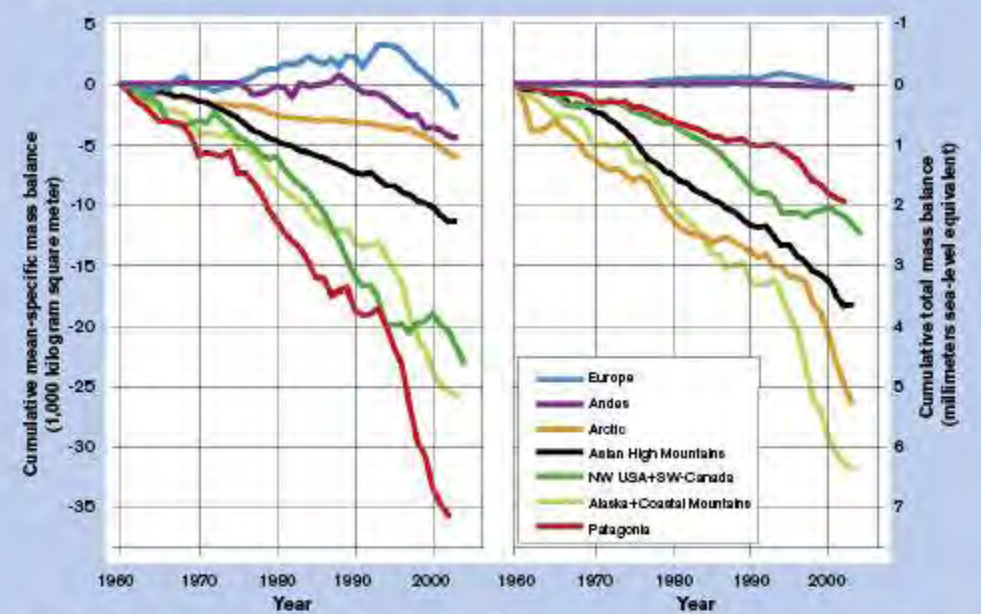
Low latitude surface waters have become markedly more saline

Water masses formed at high latitudes have become fresher

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

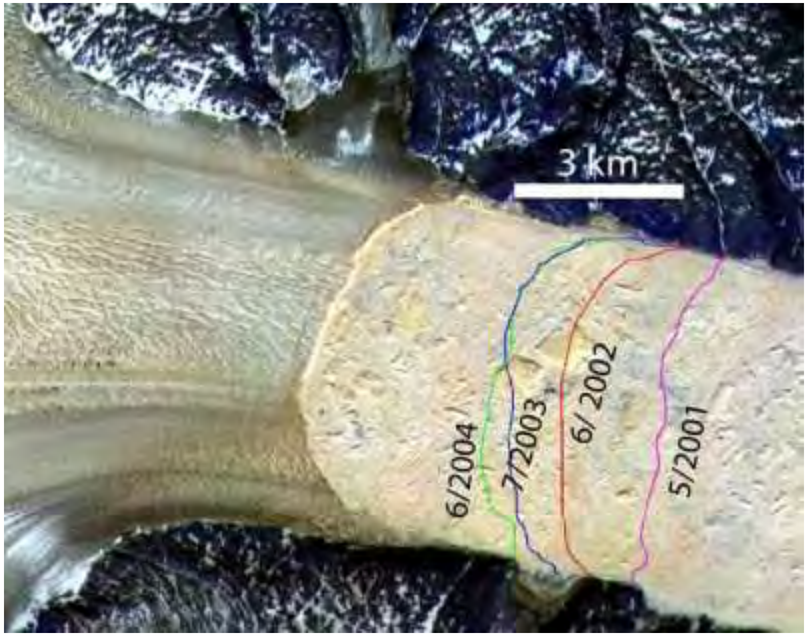
GLACIERS

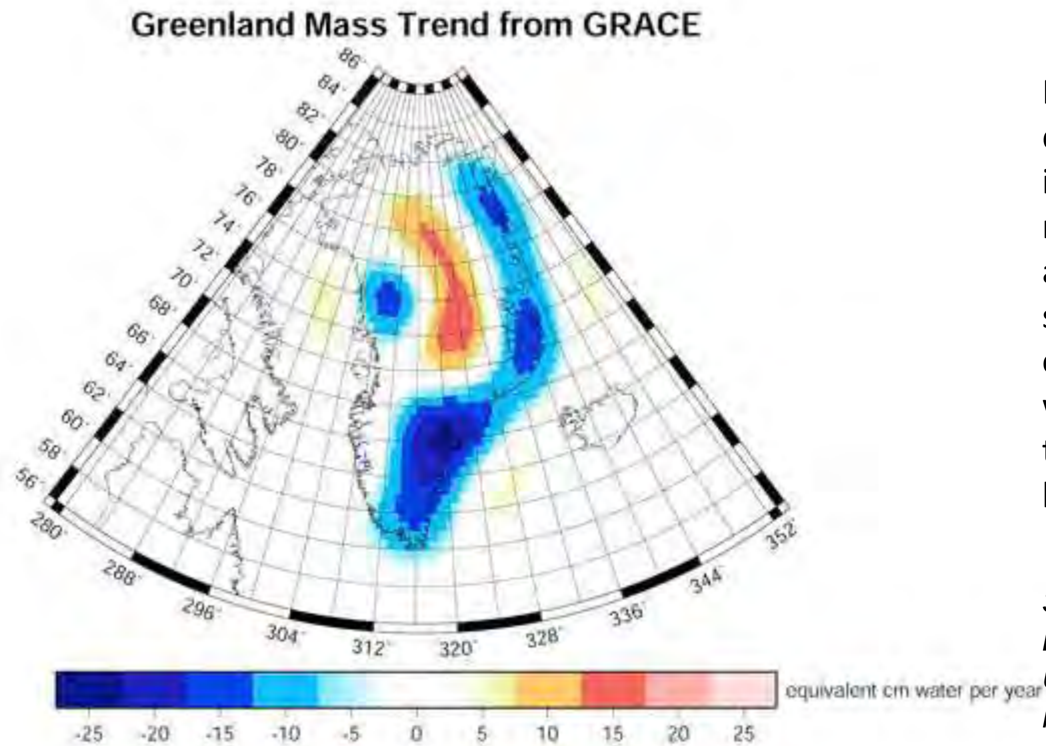
Figure 1. Glacier Trends



NOTE: The graph on the left shows the loss of glacier ice per unit area in several regions. The graph on the right shows each region's contribution to sea-level rise. Since 2000, glaciers have been shrinking in all regions, and the pace is accelerating.

SOURCE: P. Lemke et al., "Observations: Changes in Snow, Ice and Frozen Ground," in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, UK, and New York, NY: Cambridge University Press), 3,596.

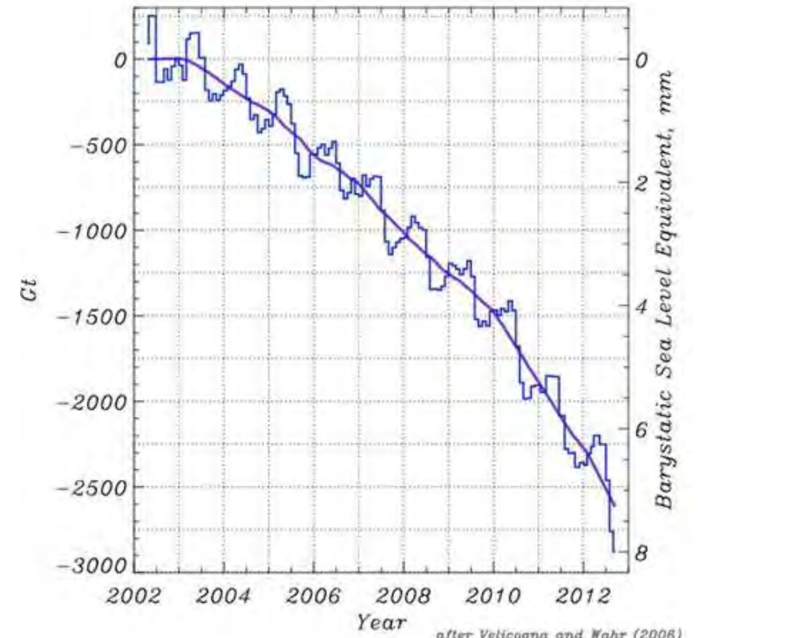




NASA satellite data has revealed regional changes in the weight of the Greenland ice sheet between 2003 and 2005. Low coastal regions (blue) lost three times as much ice per year from excess melting and icebergs than the
high-elevation interior (orange/red) gained from excess snowfall Credit: Scott Luthcke,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

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

Source: Roger Braithwaite, University of Manchester (UK)

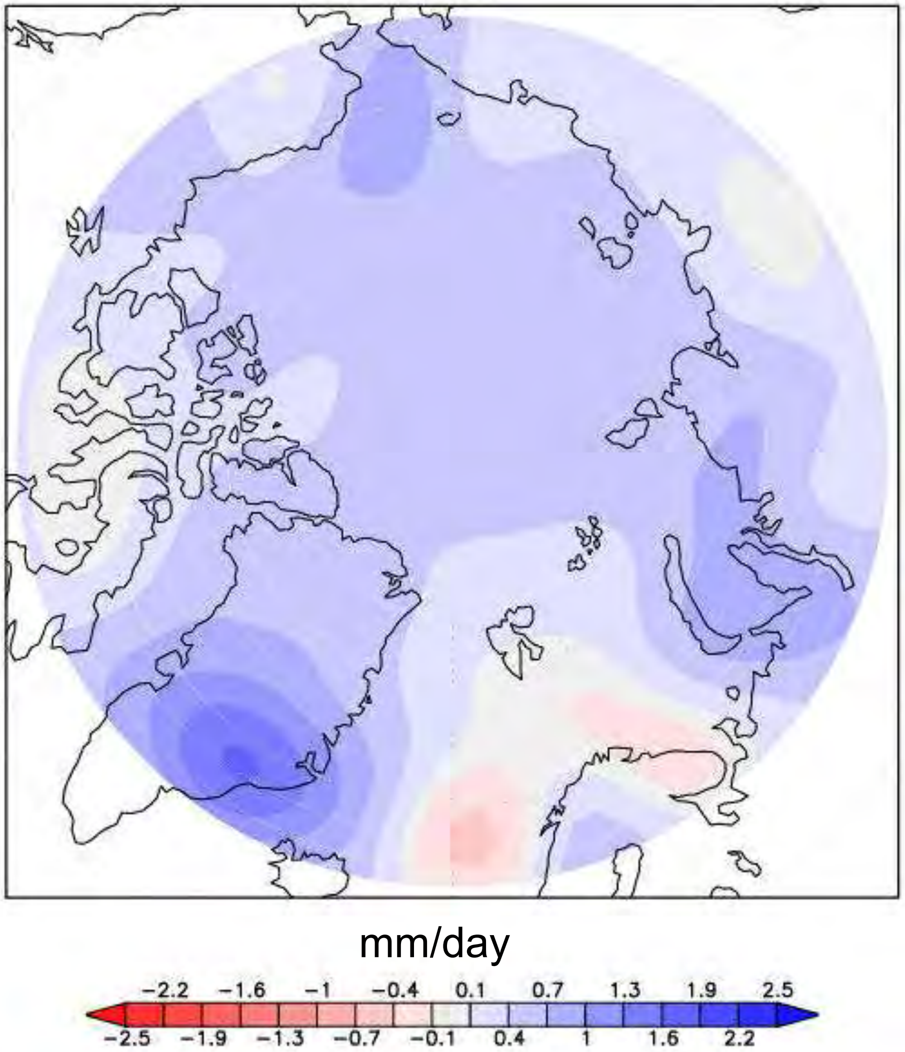


Moisture flux convergence

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

Shown here:

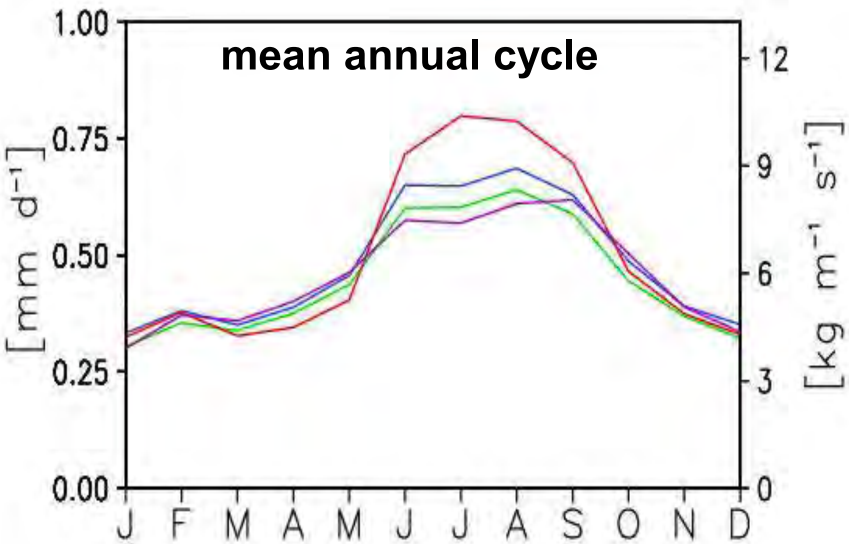
the average 1979-1993 based on mass consistent radiosonde data, smoothed to T42 (Hagenbrock 2003)

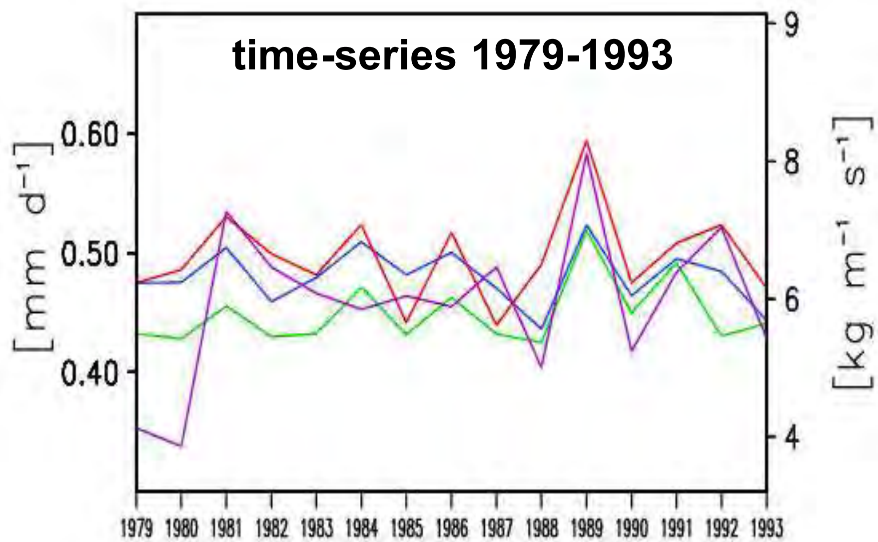


Moisture flux convergence

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

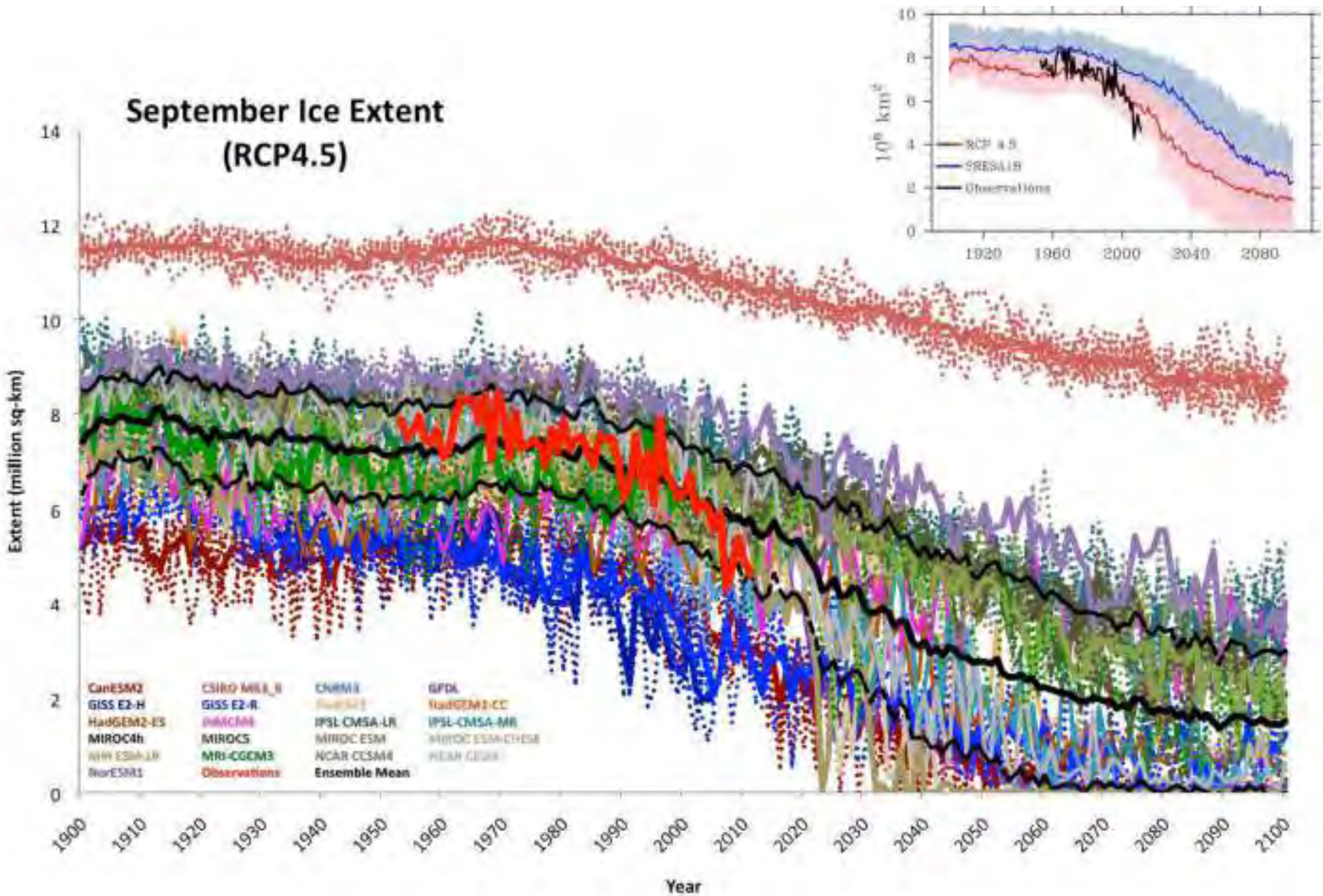
ERA-15 reanalysis data: average: 0.48 mm/d

Cullather et al.: radiosonde data: average: 0.45 mm/d

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

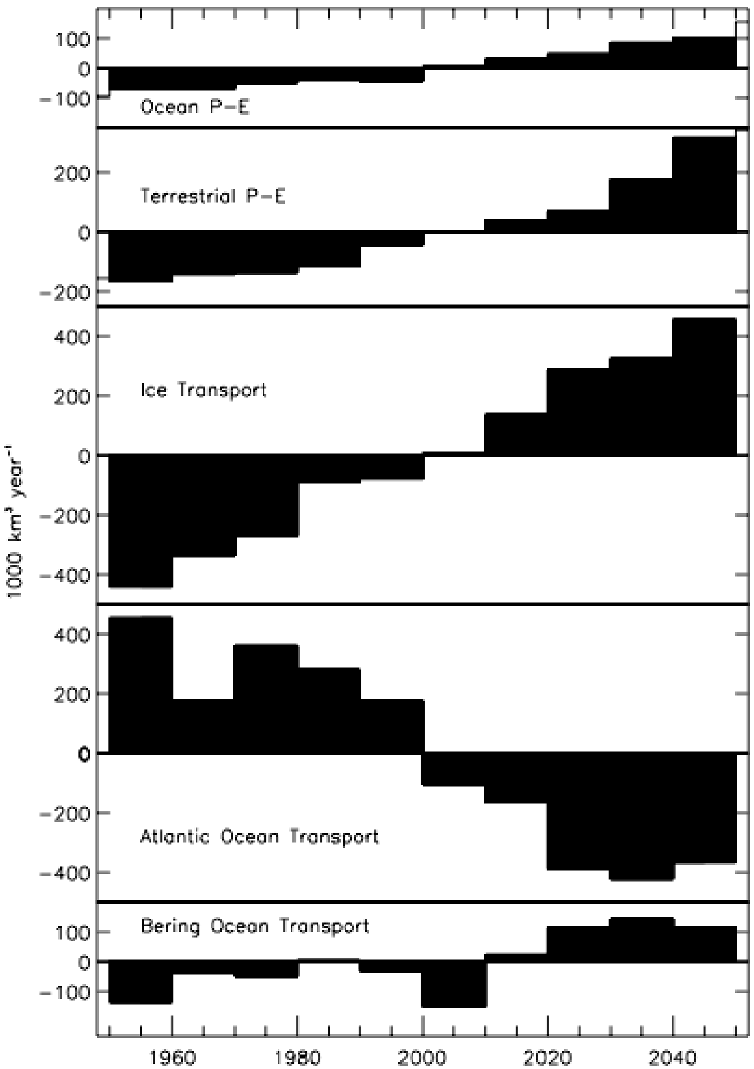
(Hagenbrock 2003, Univ. Bonn)

SEA ICE



September Ice Extent
(RCP4.5)
Extent (million sq-km)
Year
14
12
10
8
6
4
2
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
CanESM2
GISS E2-H
HadGEM2-ES
MIROC4h
NorESM1
GISS E2-R
MIROC5
MRI-CGCM3
Observations
CNRM3
IPSL CM5A-LR
MIROC ESM
NCAR CCSM4
Ensemble Mean
GFDL
HadGEM2-CC
IPSL-CM5A-MR
RCP 4.5
SRESA1B
Observations
1920
1960
2000
2040
2080

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

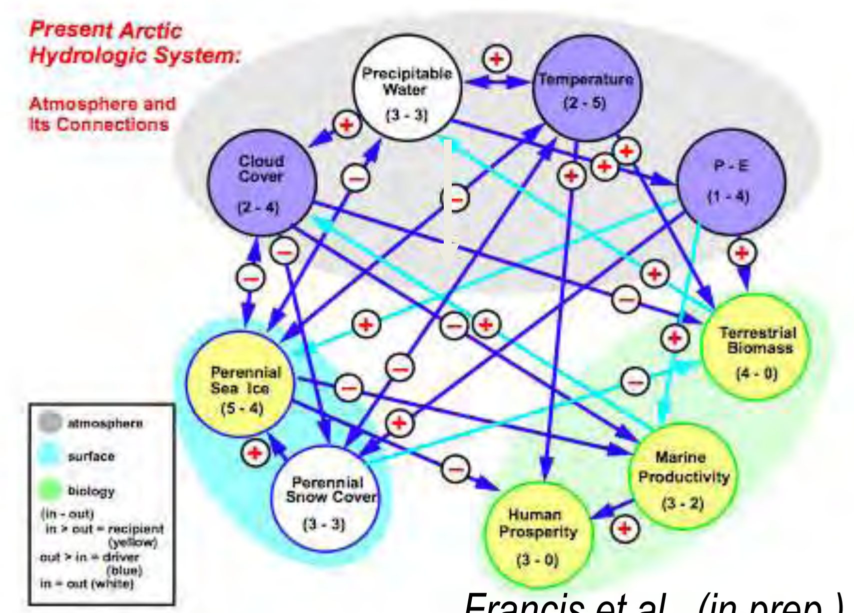
CHANGES AND ATTRIBUTION

White et al. JGR, Biogeosciences

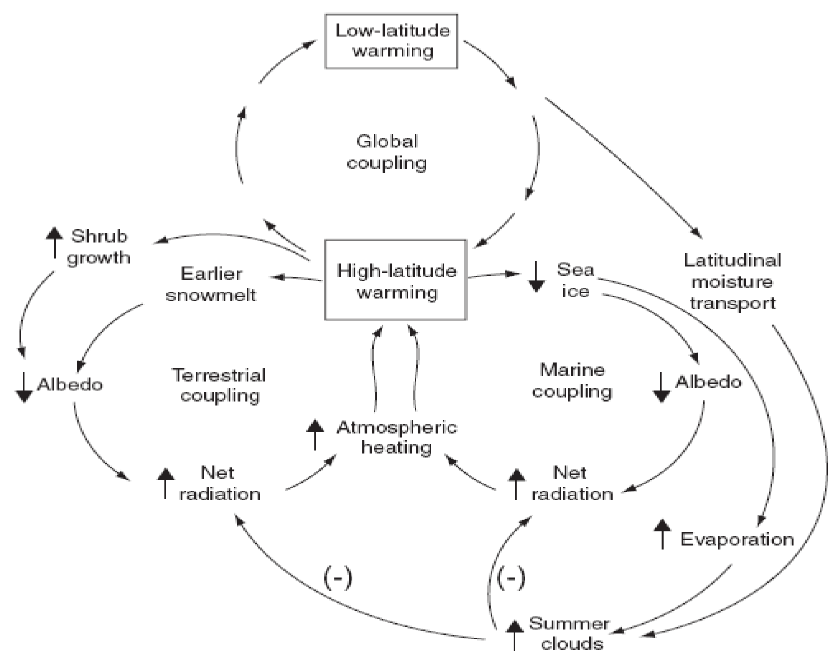
Changes in Key Stocks and Fluxes
Over "Period of Record"

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	?	?

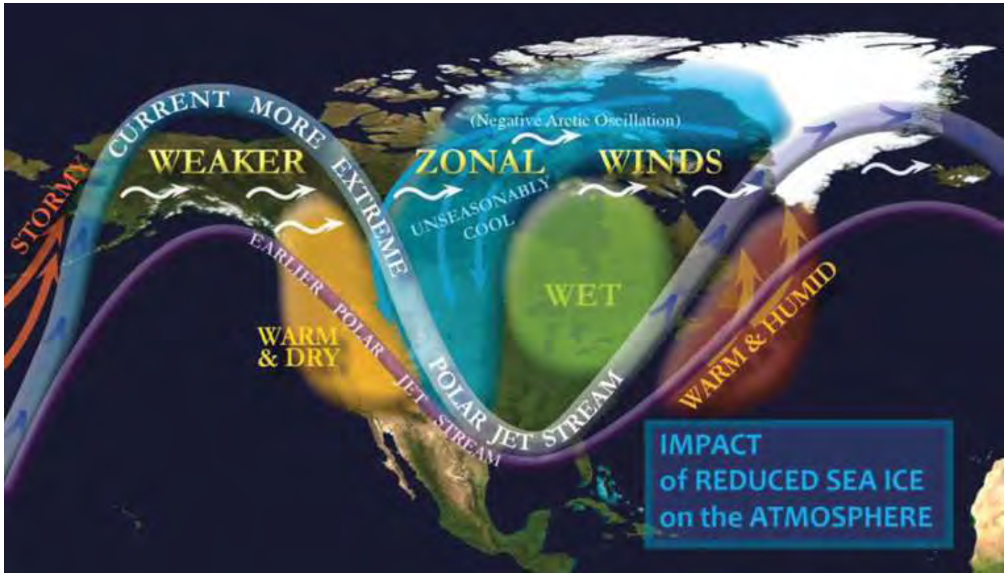
Feedbacks & implications on major subsystems

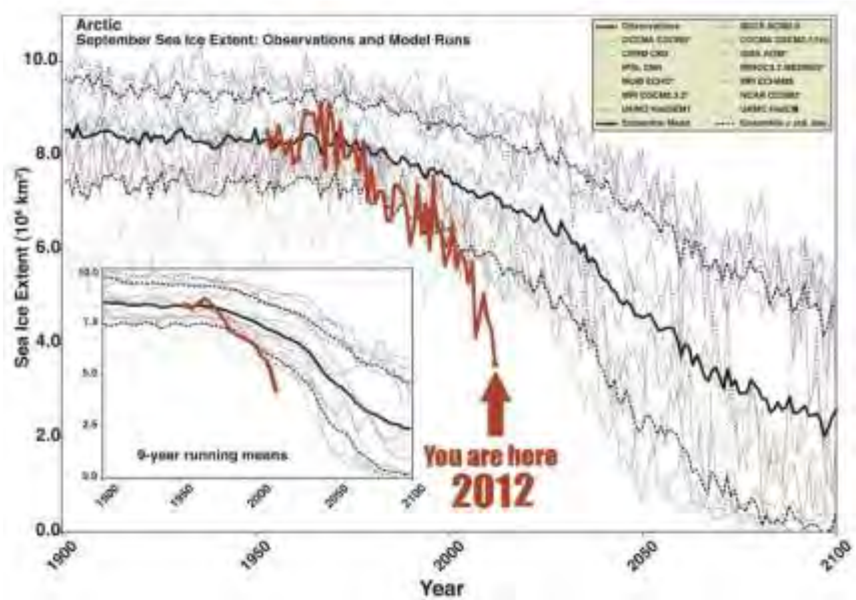


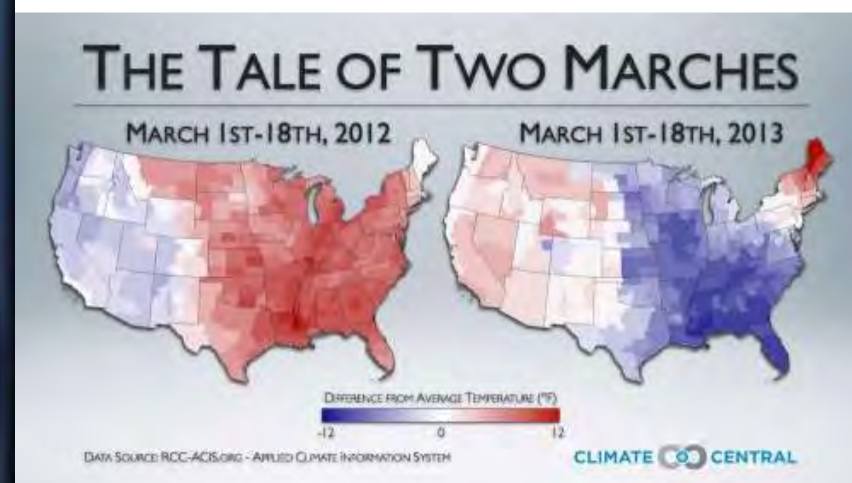
Francis et al., (in prep.)



Arctic Amplification







Arctic 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.