The Climate and The Cryosphere

ECMWF Seminar on Polar Meteorology
Reading, UK, September 4, 2006

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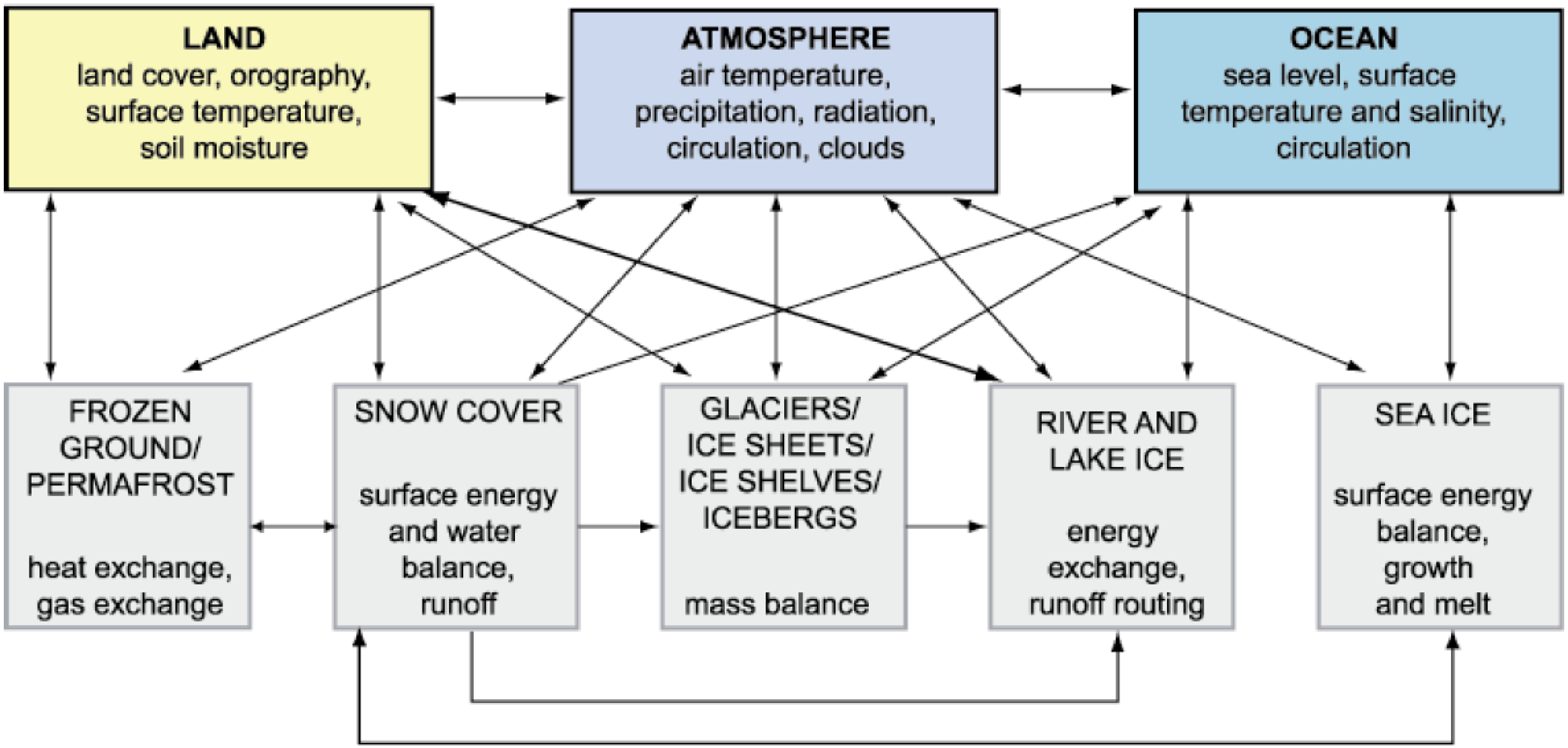
Environment Canada, and
Chair, CliC SSG

CRYOSPHERE – CLIMATE INTERACTIONS



Lists in upper boxes indicate important state variables.
Lists in lower boxes indicate important processes involved in interactions.
Arrows indicate **direct** interactions.

Media and Policy Perspectives

"A Hot Topic" on "A Cool Subject"

Inuit say spring in the Arctic is becoming more dangerous

No turning back on arctic warming

Warning for the North; Polar bears could face extinction as global climate change warms the Arctic

Melting Ice sheets, glaciers and global sea level rise

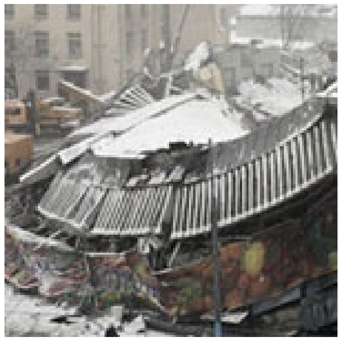
Thawing permafrost, GHG emission and coastal erosion

Farmers worried about absence of snow

Tourism at risk

Floods feared as glaciers melt

Disappearing Glaciers Menace Water Supplies

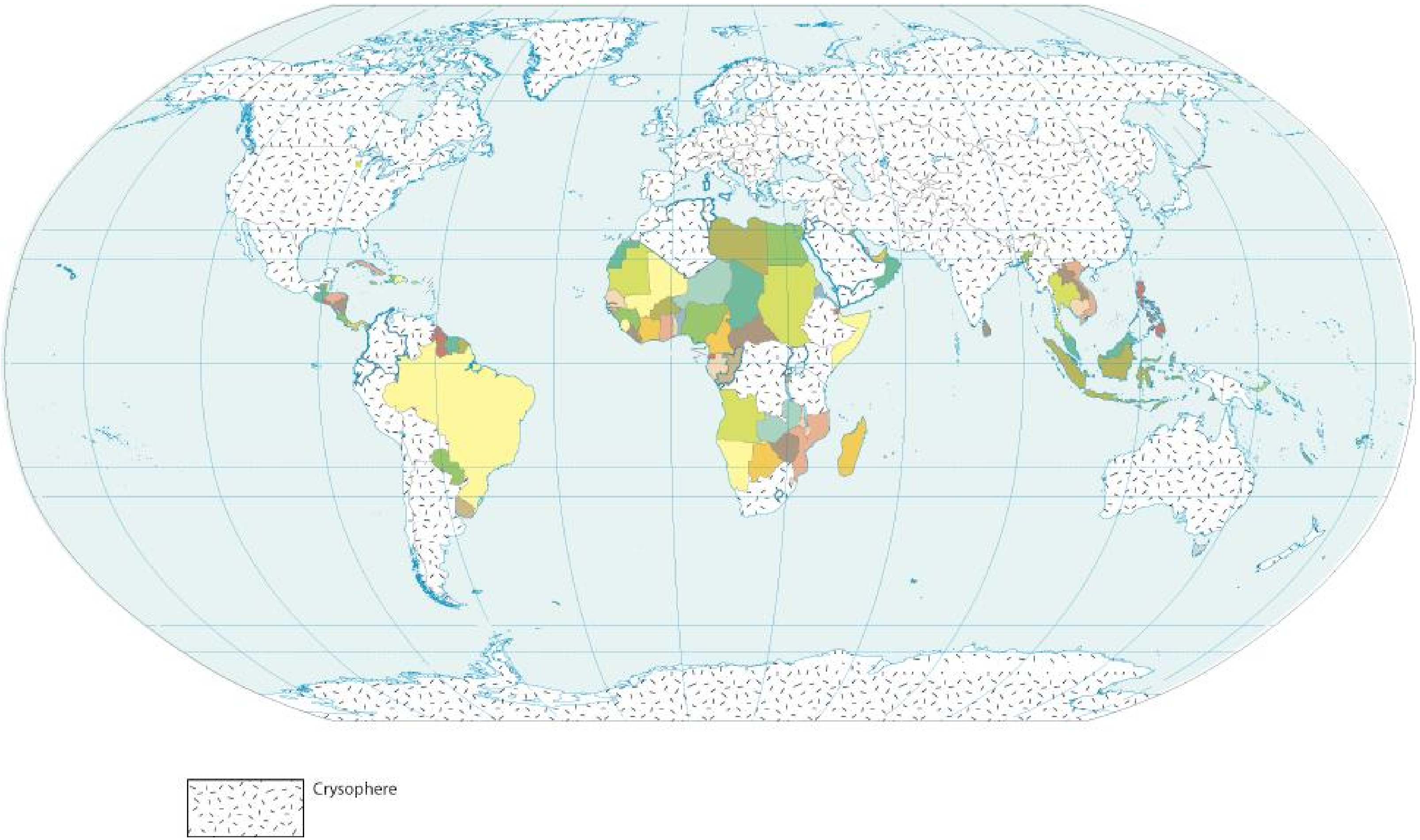


Roof collapses, Basmanny Market, Moscow

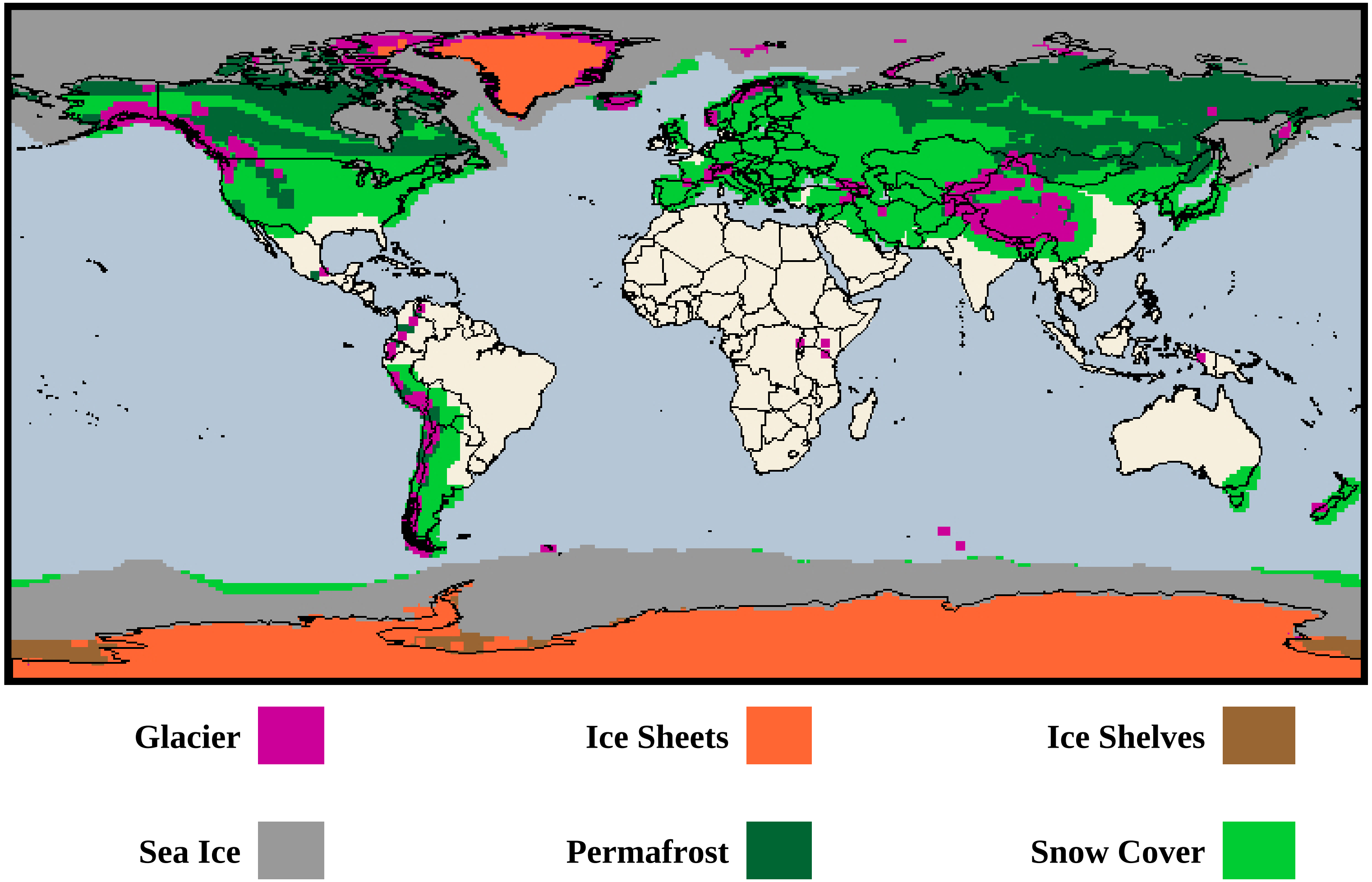
Countries Where Cryosphere Occurs

95 countries identified with cryospheric components

Cryosphere truly is global



Global Cryosphere by Type



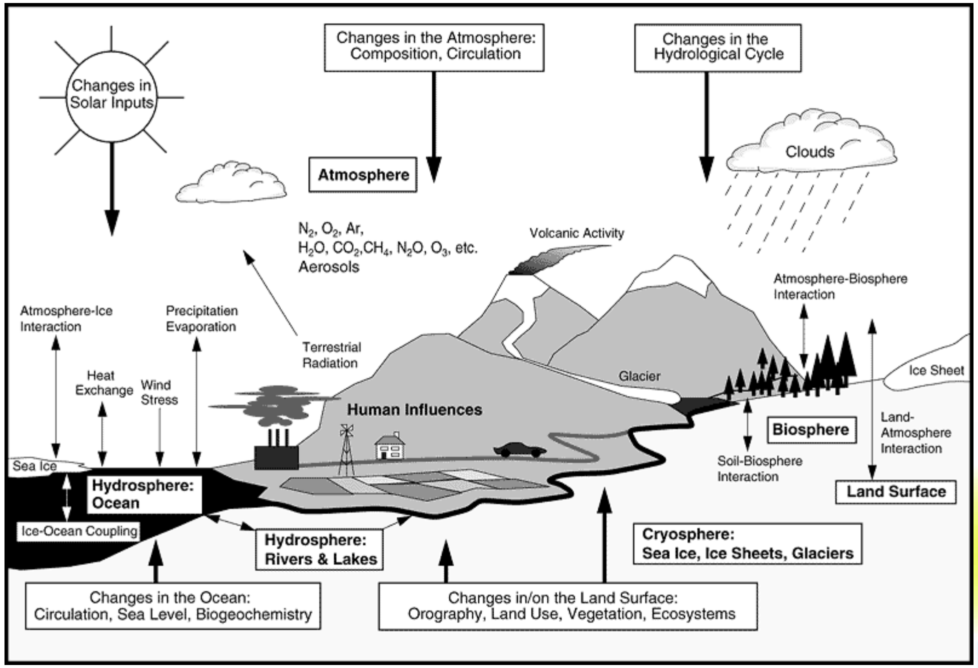
• Foster D.J. and Davy R.D., 1988: Global snow depth climatology, USAF Environmental Technical Applications Center, Note TN-88/006, 49 pp.

• Cogley, J.G., 2003: GGHYDRO – Global Hydrographic Data, Release 2.3, Trend Technical Note 2003-1, 11 pp.

Table 1

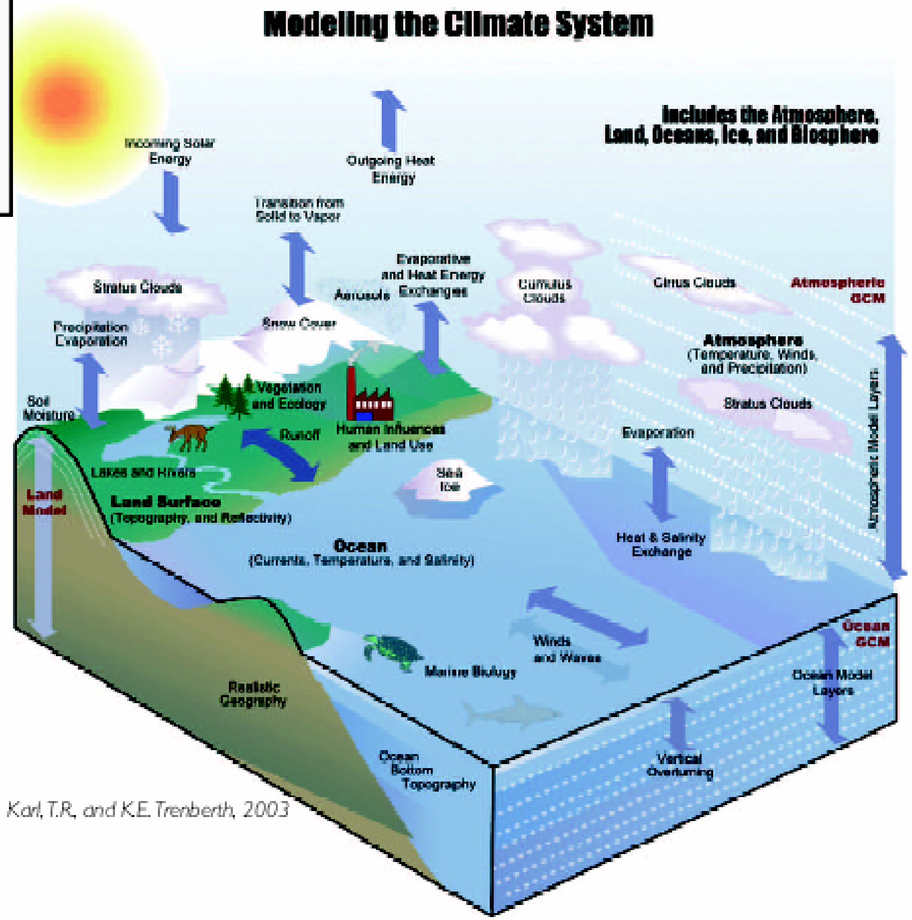
Areal and Volumetric Extent of Major Components of the Cryosphere

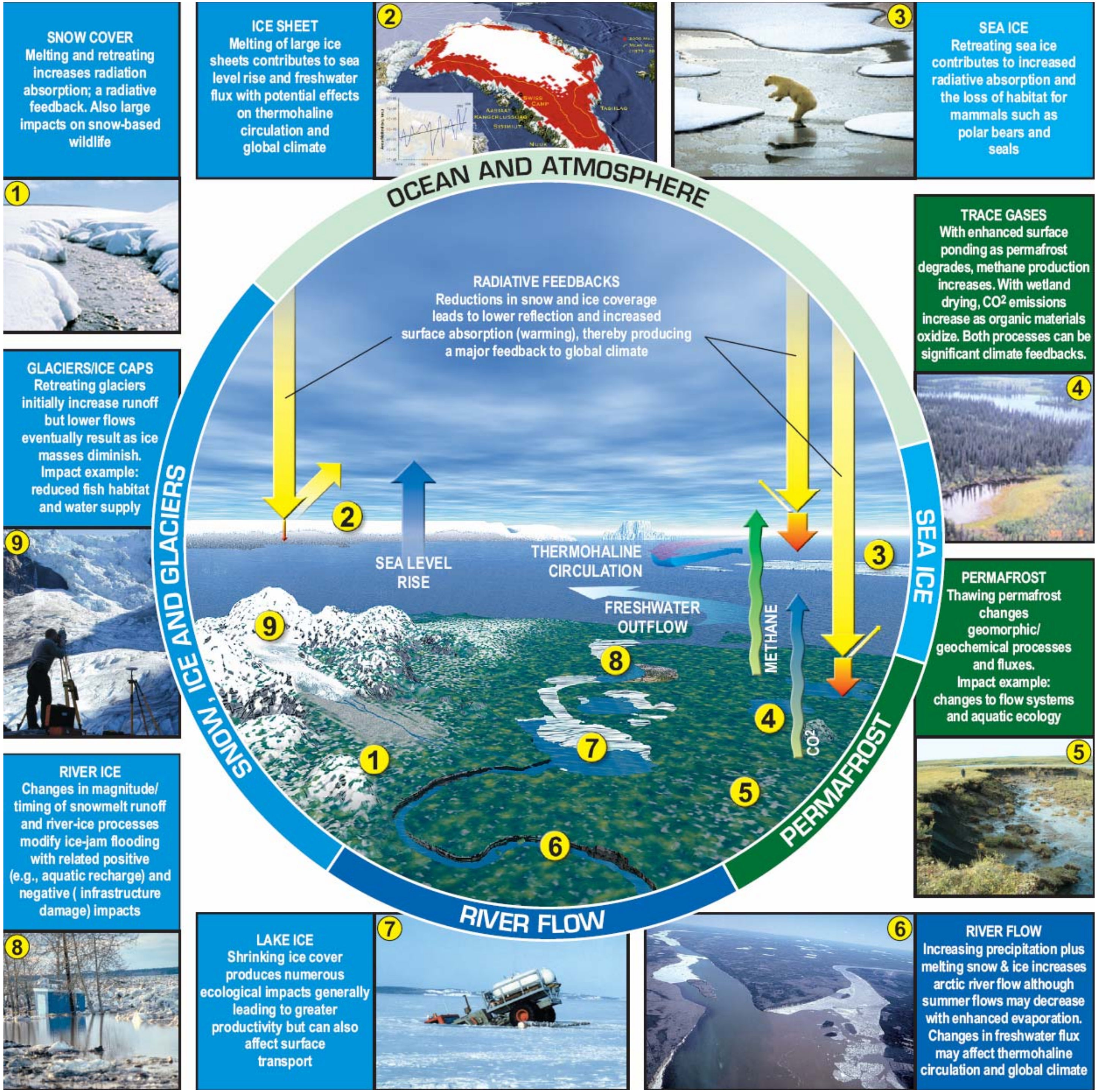
Component	Area (10^6 km^2)	Ice Volume (10^6 km^3)	Sea Level Equivalent (m) a)
LAND SNOW COVER b)			
Northern Hemisphere Late January	46.5	0.002	
Late August	3.9		
Southern Hemisphere Late July	0.85		
Early May	0.07		
SEA ICE			
Northern Hemisphere Late March	14.0 c)	0.05	
Early September	6.0 c)	0.02	
Southern Hemisphere Late September	15.0 d)	0.02	
Late February	2.0 d)	0.002	
PERMAFROST (underlying the exposed land surface, excluding Antarctica and S. Hemisphere high mountains)			
Continuous e)	10.69	0.0097-0.0250	0.024-0.063
Discontinuous and Sporadic	12.10	0.0017-0.0115	0.004-0.028
CONTINENTAL ICE AND ICE SHELVES			
East Antarctica f)	10.1	22.7	56.8
West Antarctica and Antarctic Peninsula f)	2.3	3.0	7.5
Greenland g)	1.8	2.6	6.6
Small Ice Caps and Mountain Glaciers h)	0.68	0.18	0.5
Ice Shelves f)	1.5	0.66	—



IPCC TAR. Scientific Basis. Section 1.1.2 The Climate System

Figure 1.1: *Schematic view of the components of the global climate system (bold), their processes and interactions (thin arrows) and some aspects that may change (bold arrows).*




SNOW COVER
Melting and retreating increases radiation absorption; a radiative feedback. Also large impacts on snow-based wildlife
ICE SHEET
Melting of large ice sheets contributes to sea level rise and freshwater flux with potential effects on thermohaline circulation and global climate
SEA ICE
Retreating sea ice contributes to increased radiative absorption and the loss of habitat for mammals such as polar bears and seals
TRACE GASES
With enhanced surface ponding as permafrost degrades, methane production increases. With wetland drying, CO2 emissions increase as organic materials oxidize. Both processes can be significant climate feedbacks.
GLACIERS/ICE CAPS
Retreating glaciers initially increase runoff but lower flows eventually result as ice masses diminish. Impact example: reduced fish habitat and water supply
PERMAFROST
Thawing permafrost changes geomorphic/ geochemical processes and fluxes. Impact example: changes to flow systems and aquatic ecology
RIVER ICE
Changes in magnitude/ timing of snowmelt runoff and river-ice processes modify ice-jam flooding with related positive (e.g., aquatic recharge) and negative (infrastructure damage) impacts
LAKE ICE
Shrinking ice cover produces numerous ecological impacts generally leading to greater productivity but can also affect surface transport
RIVER FLOW
Increasing precipitation plus melting snow & ice increases arctic river flow although summer flows may decrease with enhanced evaporation. Changes in freshwater flux may affect thermohaline circulation and global climate
OCEAN AND ATMOSPHERE
SEA ICE
PERMAFROST
RIVER FLOW
SNOW, ICE AND GLACIERS
RADIATIVE FEEDBACKS
Reductions in snow and ice coverage leads to lower reflection and increased surface absorption (warming), thereby producing a major feedback to global climate
SEA LEVEL RISE
THERMOHALINE CIRCULATION
FRESHWATER OUTFLOW
METHANE
CO2
1
2
3
4
5
6
7
8
9

Global Cryosphere – need for good observations, measurements and models

Snow

- SWE, depth, extent, state, density, snowfall, solid precipitation, albedo
- in-situ climate & synoptic (manual, auto), weather radar, remote sensing

Sea Ice

- extent, concentration, open water, type, thickness, motion, icebergs, snow on ice
- landfast (manual), ship-based & aerial reconnaissance, satellite & airborne reconnaissance

Lake and River Ice

- FU/BU, thickness, snow on ice
- in-situ (shore based), remote sensing

Glaciers, Ice Caps, Ice sheets

- mass balance (accumulation/ablation), thickness, area, length (geometry), firn temperature, snowline/equilibrium line, snow on ice
- ground-based (in-situ), remote sensing

Frozen Ground/Permafrost

- soil temperature/thermal state, active layer thickness, borehole temperature, extent, snow cover
- in-situ, remote sensing (new)

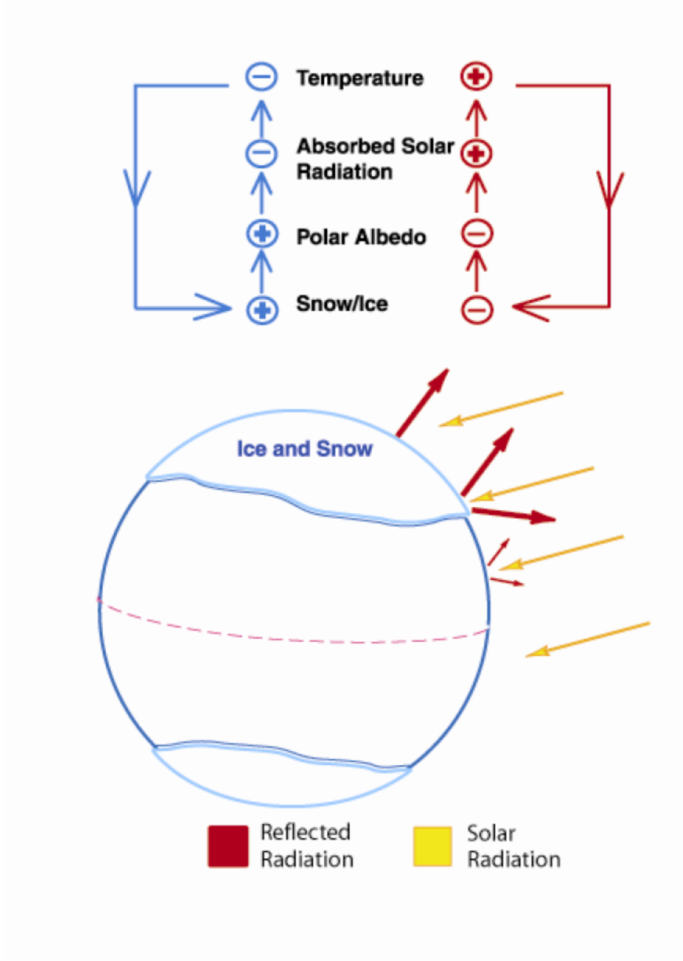


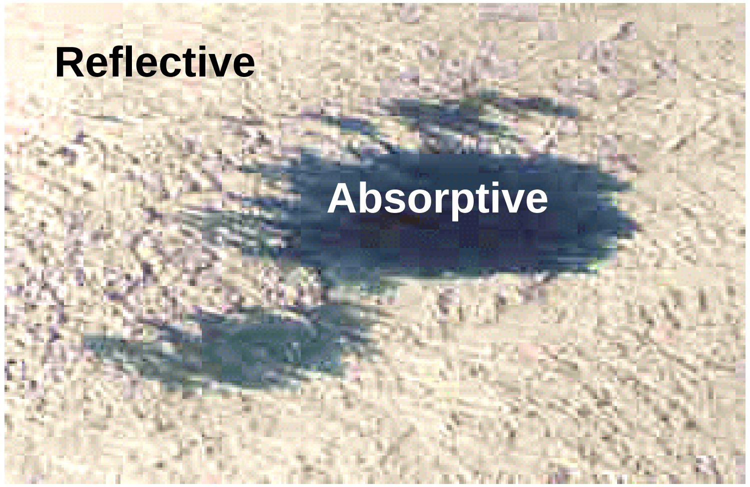
Figure 2. Snow-ice/albedo feedback

The snow-ice/albedo feedback *(Figure 2)* and the permafrost/greenhouse gas amplification would both enhance any initial warming.

Ice sheet/glacier/snow melting also provides a positive feedback

- **Decreased albedo**
- **Increased evaporation**

Tendency of melt is to enhance melting



CliC Goal and Objectives

Principal Goal:

To assess and quantify the impacts that climatic variability and change have on components of the cryosphere and the consequences of these impacts for the climate system.

In addressing this aim, CliC also seeks to determine the stability of the global cryosphere

Supporting Objectives:

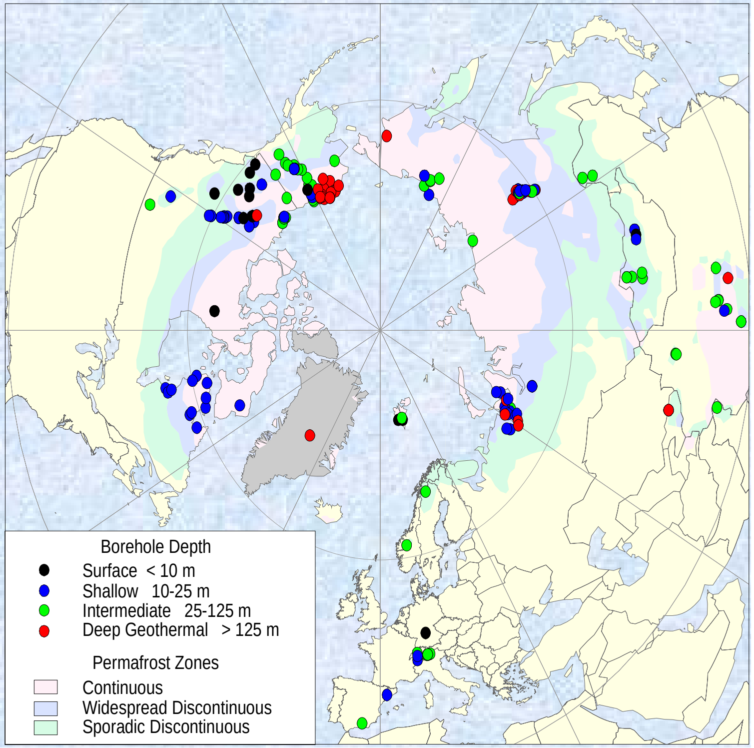
- ***Enhance the observation and monitoring of the cryosphere and the climate of cold regions in support of process studies, model evaluation, and change detection.***
- ***Improve understanding of the physical processes and feedbacks through which the cryosphere interacts within the climate system***
- ***Improve the representation of cryospheric processes in models to reduce uncertainties in simulation of climate and predictions of climate change (role of the cryosphere on predictability of the climate system)***
- ***Facilitate assessment of changes in the cryosphere and their impact, and to use this information to aid the detection of climate change***

CPA1. The Terrestrial cryosphere and hydrometeorology of cold regions

Central questions:

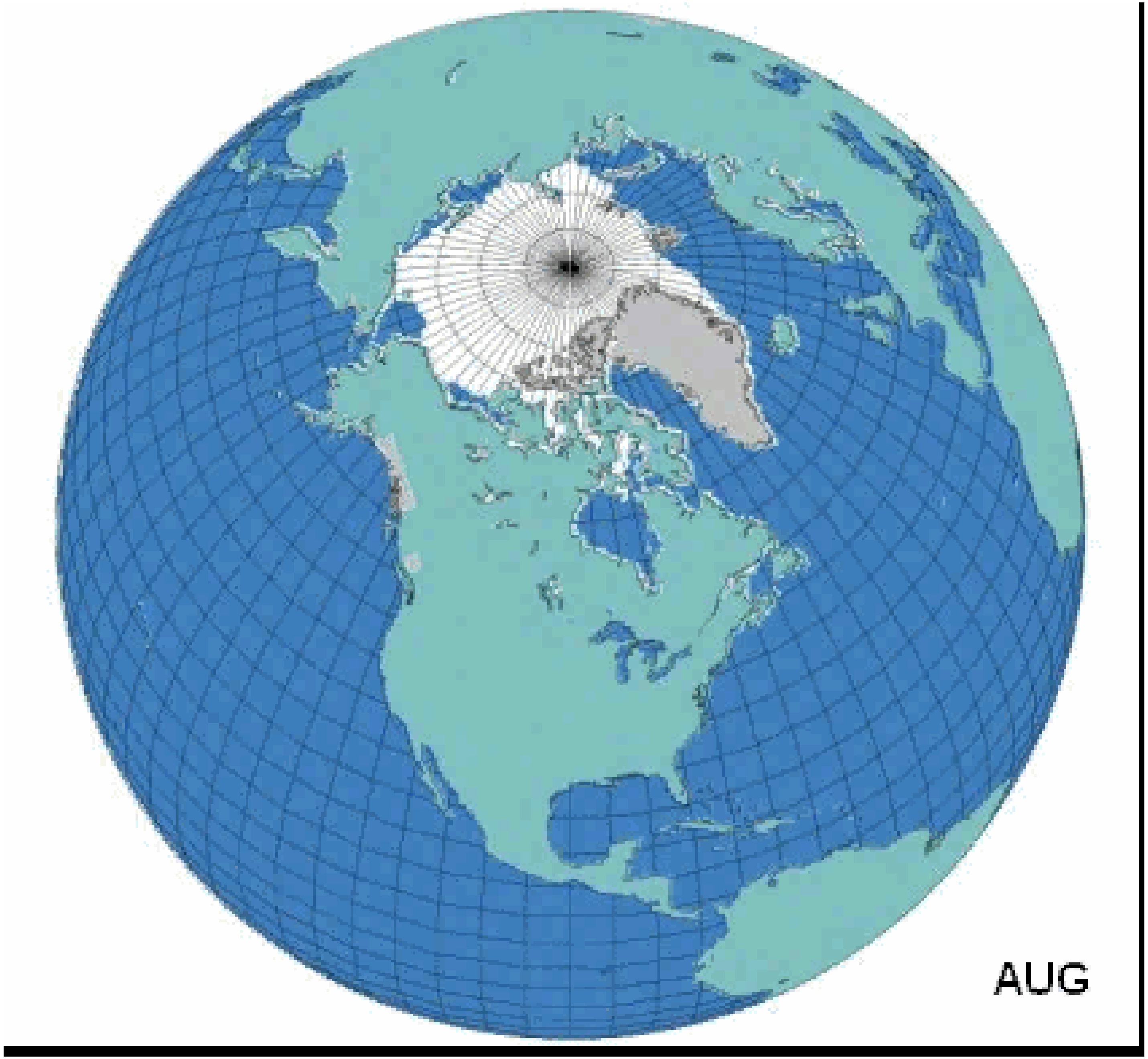
- ***What will be the magnitudes, patterns and rates of change in terrestrial cryosphere regimes on seasonal to century time scales? What will be the associated changes in the water cycle?***
- ***What is the role of terrestrial cryospheric processes in the spatial and temporal variability of the water, energy and carbon cycle of cold climate regions, and how can they be parameterized in models?***
- ***What are the interactions and feedback between the terrestrial cryosphere and atmosphere/ocean systems and current climates, its variability and future change?***

Boreholes Eligible for GTN-P

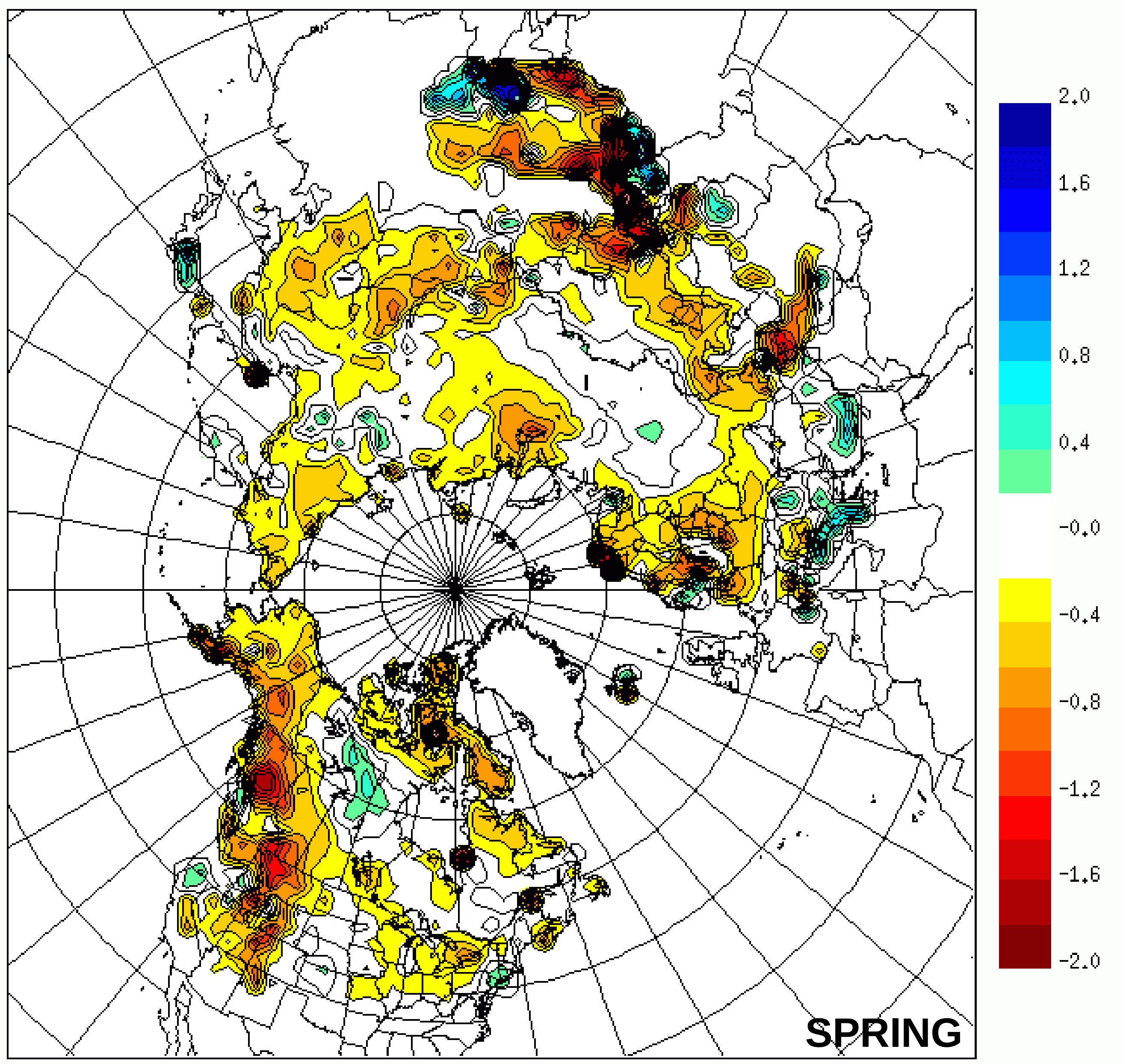


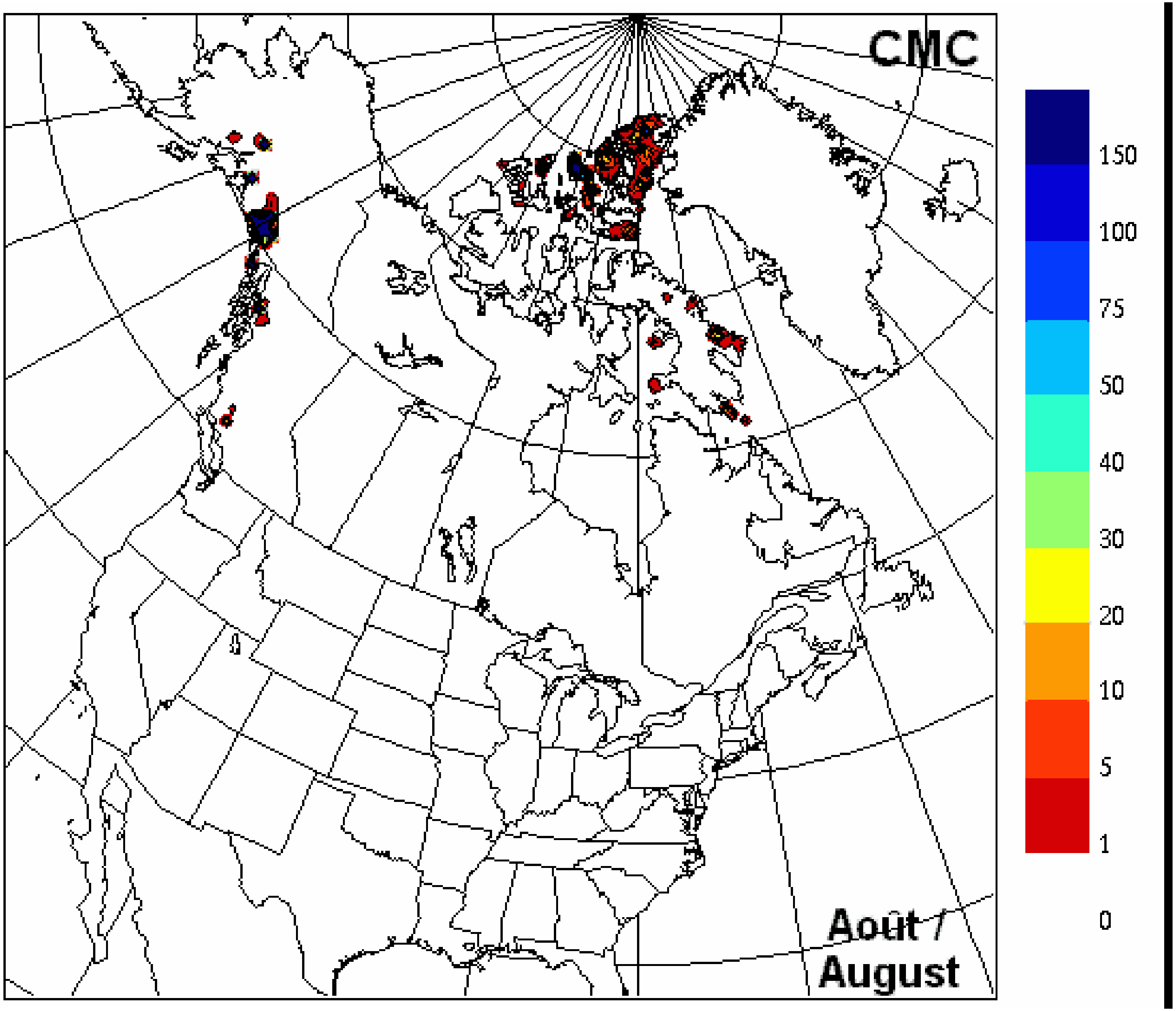
Outputs: (solid precip, snow, lake- and river-ice, glaciers, permafrost, frozen ground)

- **Spatial-temporal variability**
- **Changes in the cryosphere and water cycle**
- **Observations and data**
- **Modelling**


AUG

Observed change (days/yr) in snow cover duration from the NOAA weekly satellite product, 1966 to 2004

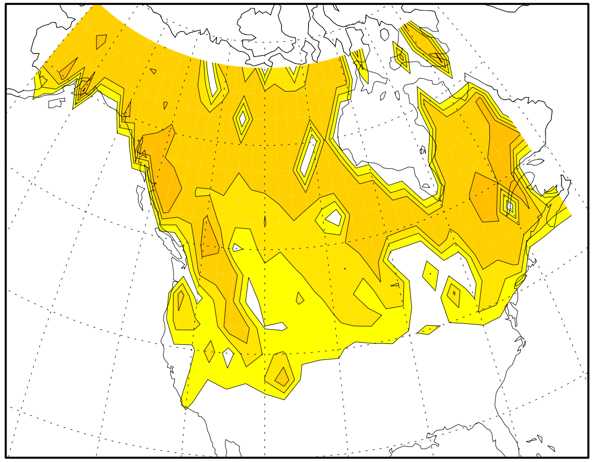



CMC
150
100
75
50
40
30
20
10
5
1
0
Août /
August

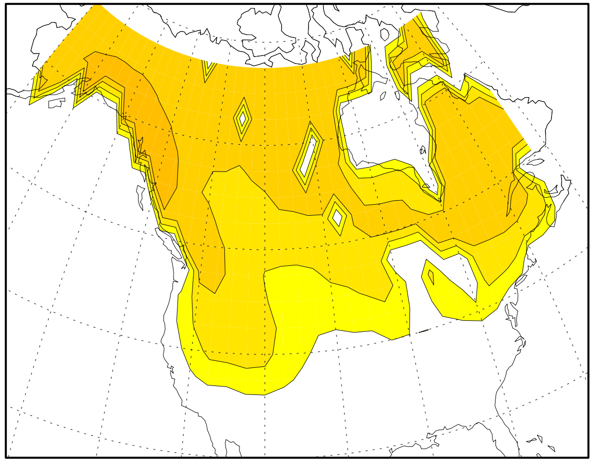
Representation of snow cover and snow cover climate feedbacks in climate models

- AMIP2 - Ensemble of 17 AGCMs provided a **reasonable simulation of the monthly SWE <u>climatology</u>** for NA but the **models were unable to capture the observed interannual variability in SWE**

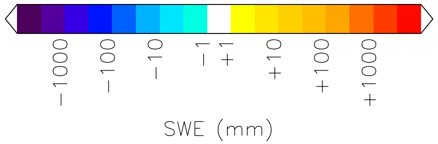
- more work is needed

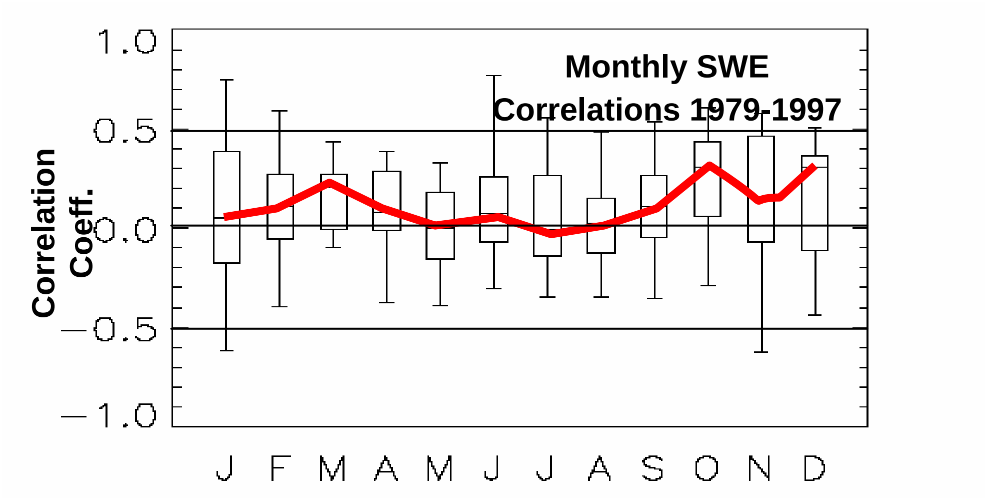


OBS seasonal mean SWE Oct-June (re-gridded to 2.5 degrees)



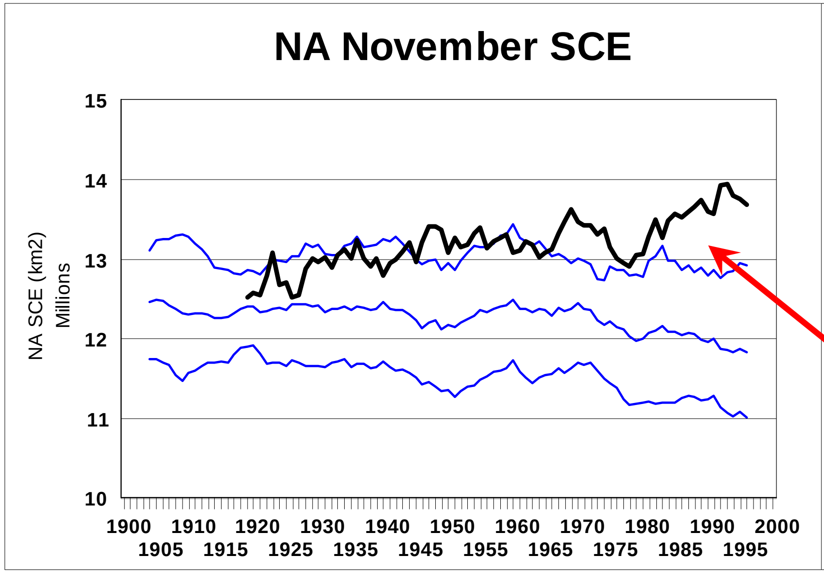
Median SWE from 17 model ensemble

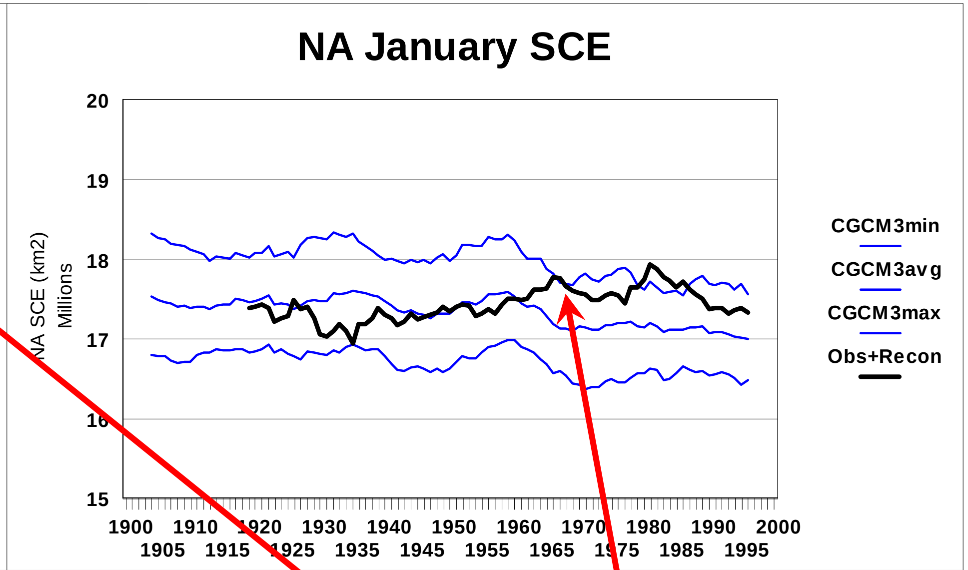


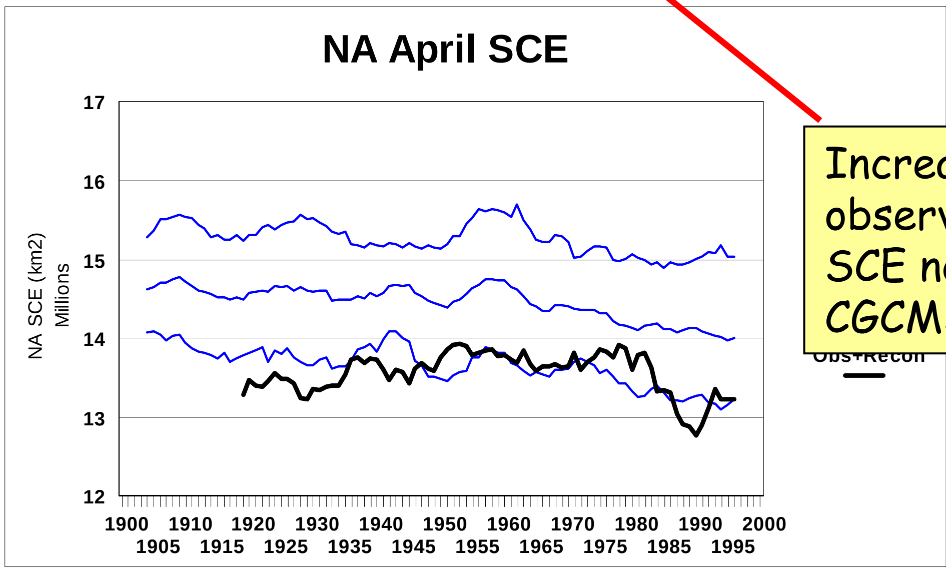


Frei, Brown, Miller, Robinson 2005: Snow mass over North America: observations and results from the second phase of the Atmospheric Model Intercomparison Project (AMIP-2) J. Hydromet.

Comparison of observed (Brown, 2000) and simulated 20th C snow cover extent



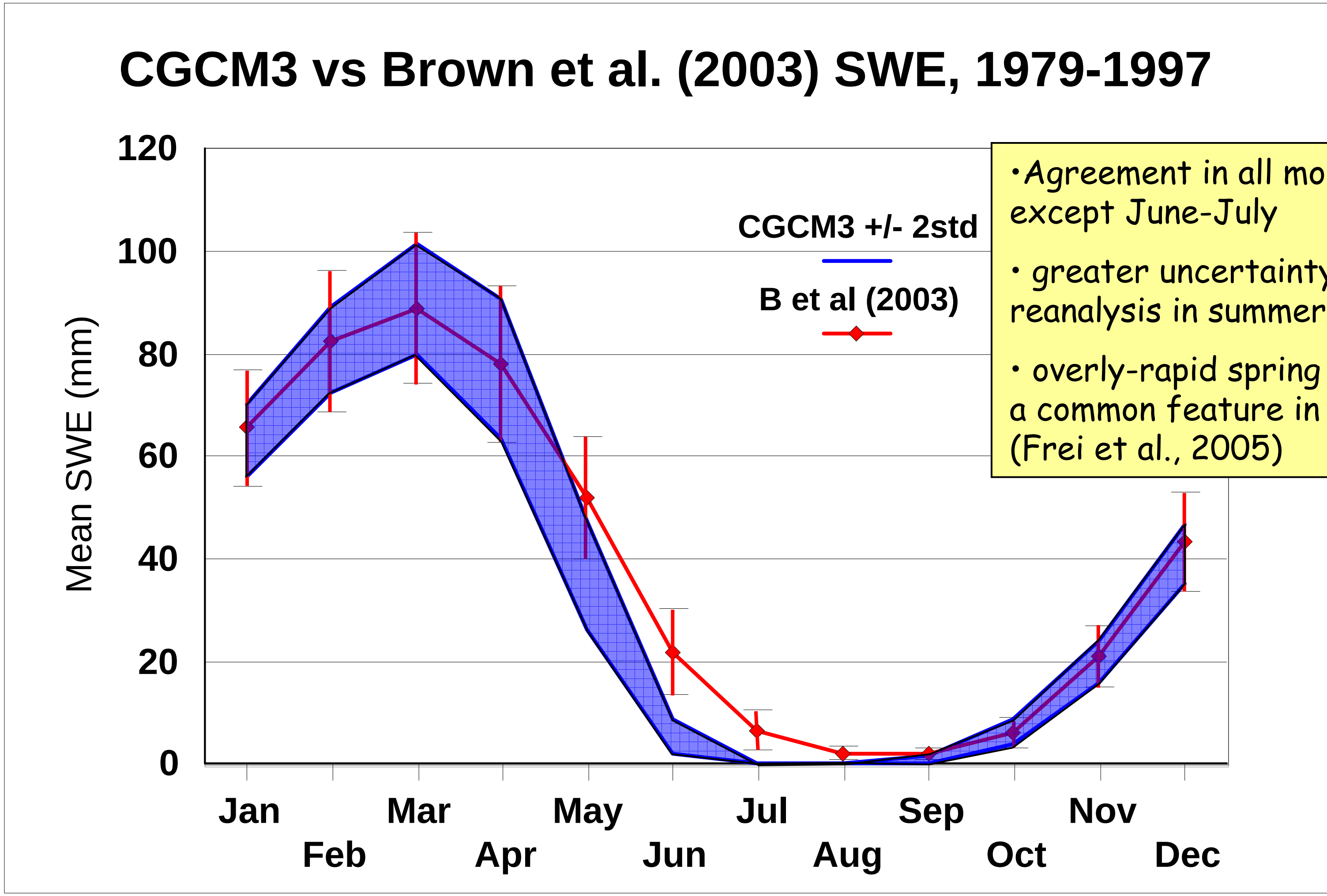




- All 5 20C3M runs show significant 20th C reductions in NA SCE from April-October
- decrease most noticeable after ~1960 (similar to observed and modelled sea-ice extent)

Increasing trend in observed Nov-Jan SCE not captured by CGCM3

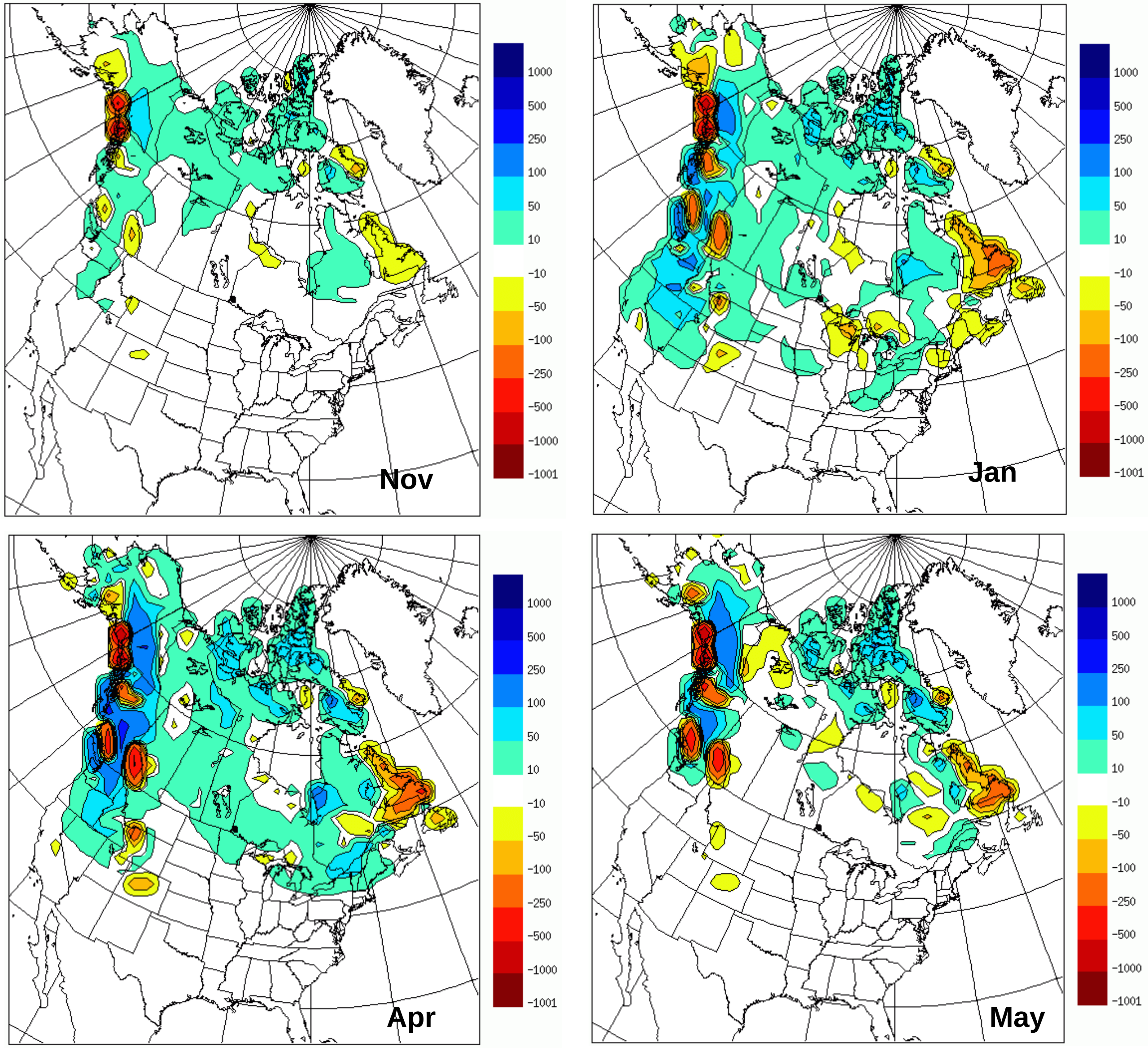
Seasonal evolution of NA mean SWE from 5x20C3M runs of CGCM3



- Agreement in all months except June-July
- greater uncertainty in SWE reanalysis in summer months
- overly-rapid spring ablation a common feature in GCMs (Frei et al., 2005)

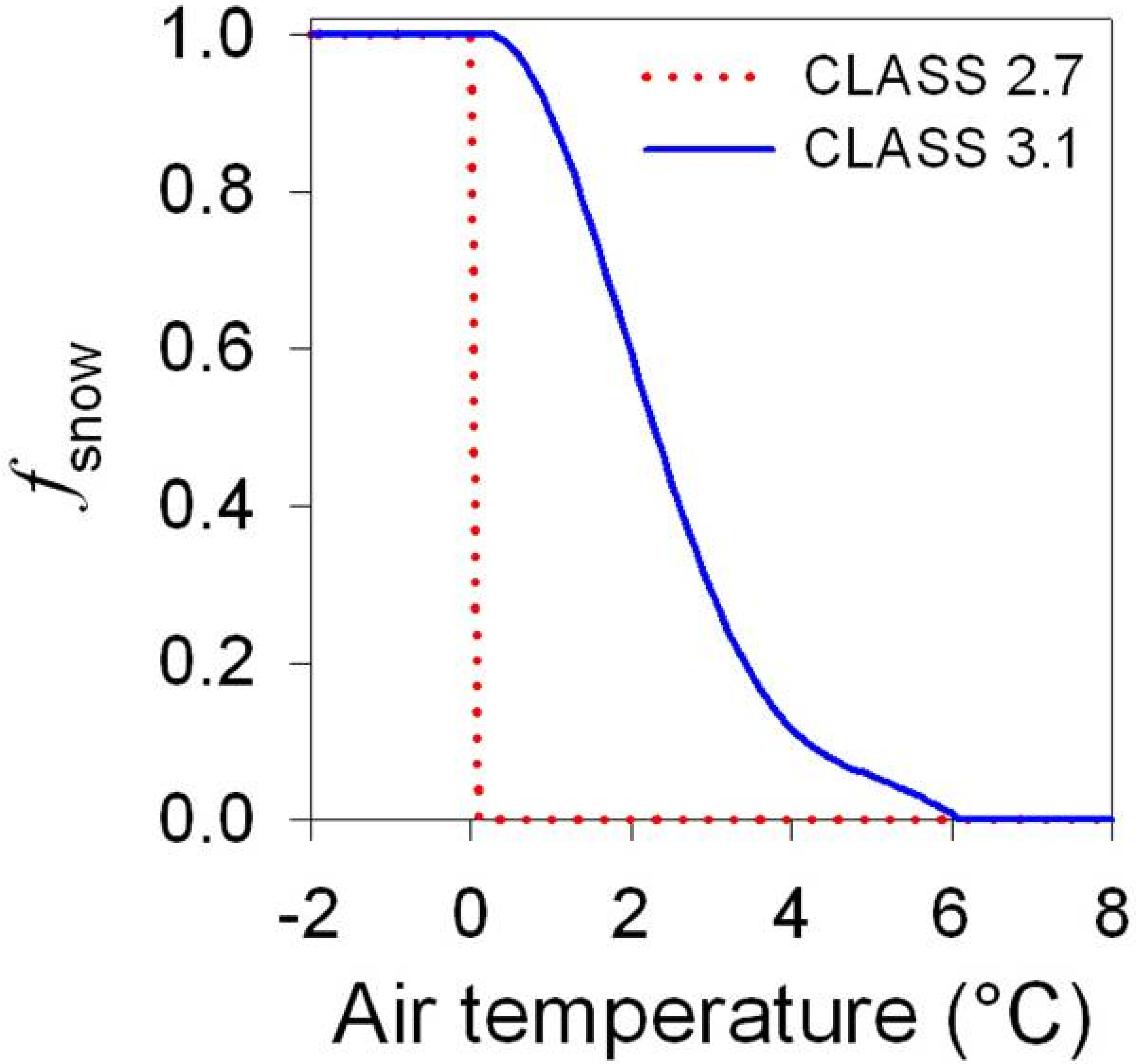
CGCM3 provides a reasonable representation of the 20th C snow cover climatology of NA (with the exception of snow density) and has **realistic interannual variability** and snow cover temperature sensitivity

Difference in 1979-1997 mean monthly SWE (mm) between SWE average from 5 CGCM3 runs and Brown et al. (2003) (CGCM3 minus B2003)



- Over most of NA continent, SWE differences are within +/- 10 mm
- Large under-prediction around Rockies related to topography and interpolation process
- Large under-prediction over Labrador (partly an interpolation issue but also identified by Frei et al. 2005 as a common feature in the AMIP-2 AGCMs)
- Regional underestimates of SWE in Rockies and Labrador influence continental average in spring (are regions with the largest spring SWE)

Mixed precipitation



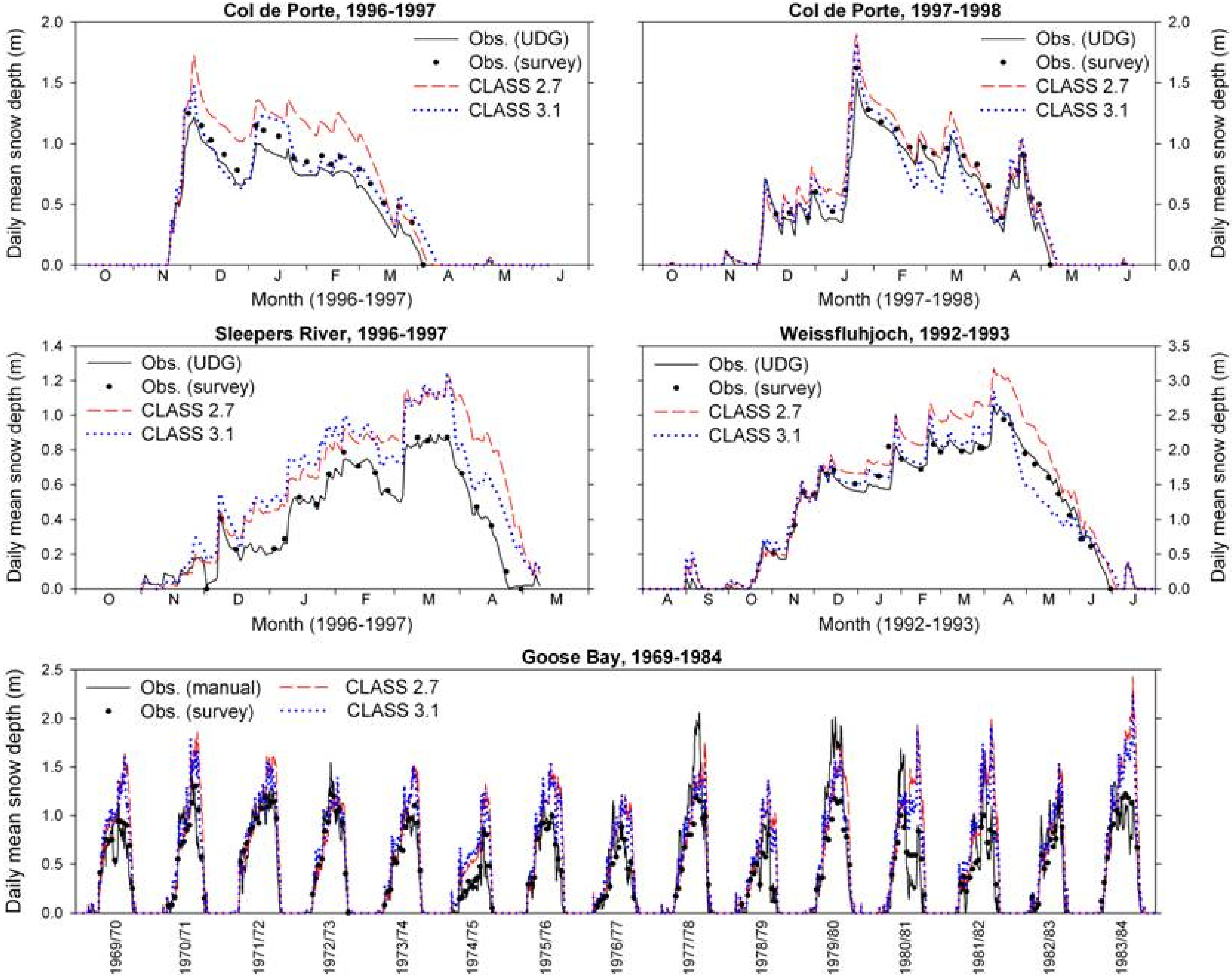
CLASS 2.7:
Precipitation is diagnosed as rain or snow using a simple threshold air temperature of 0°C.

CLASS 3.1:
The fraction of precipitation that is snow is modelled using a polynomial, which allows mixed precipitation between 0° and 6°C.

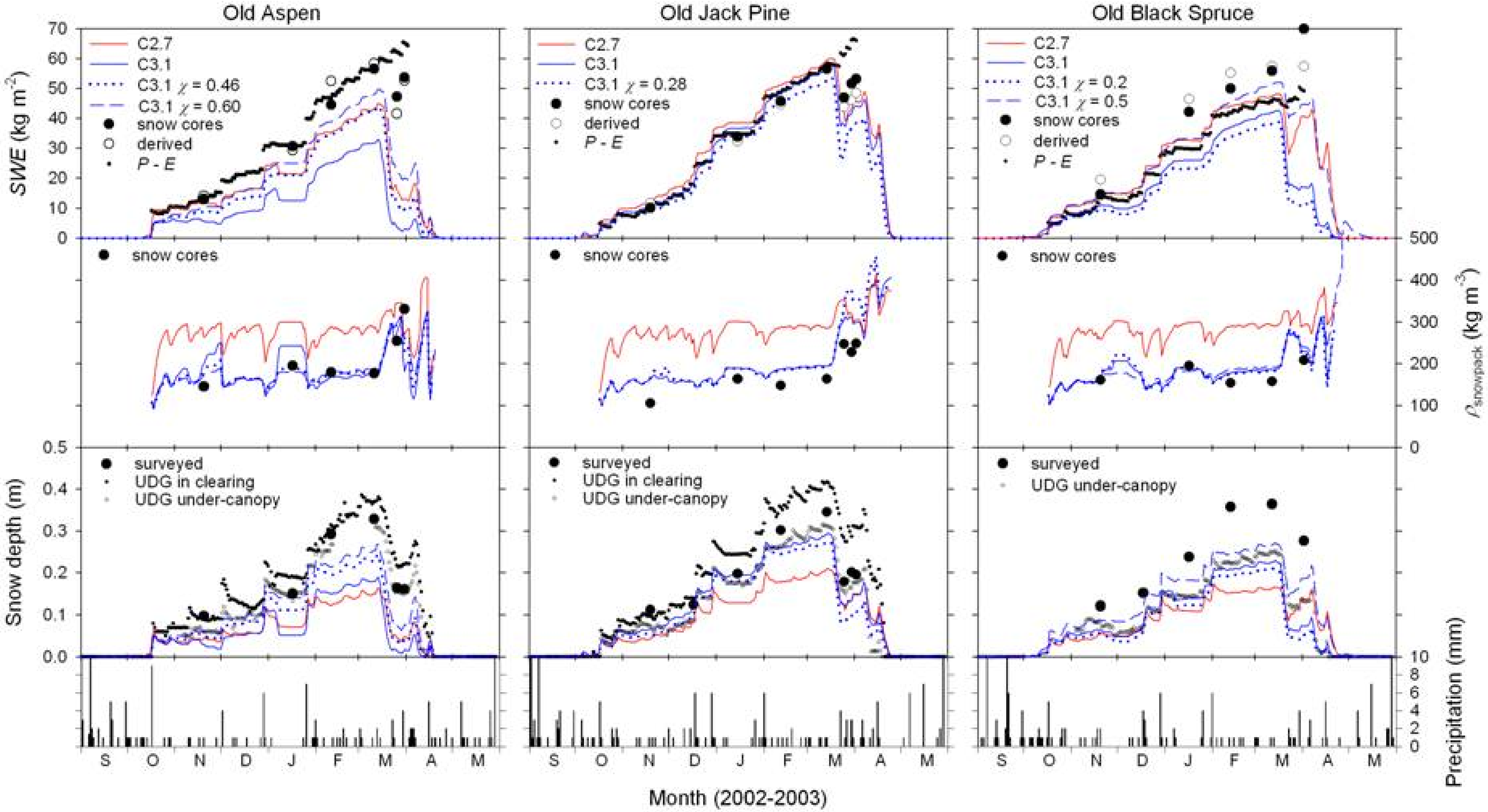
(Auer, 1974)

Courtesy, Paul Bartlett, Environment Canada

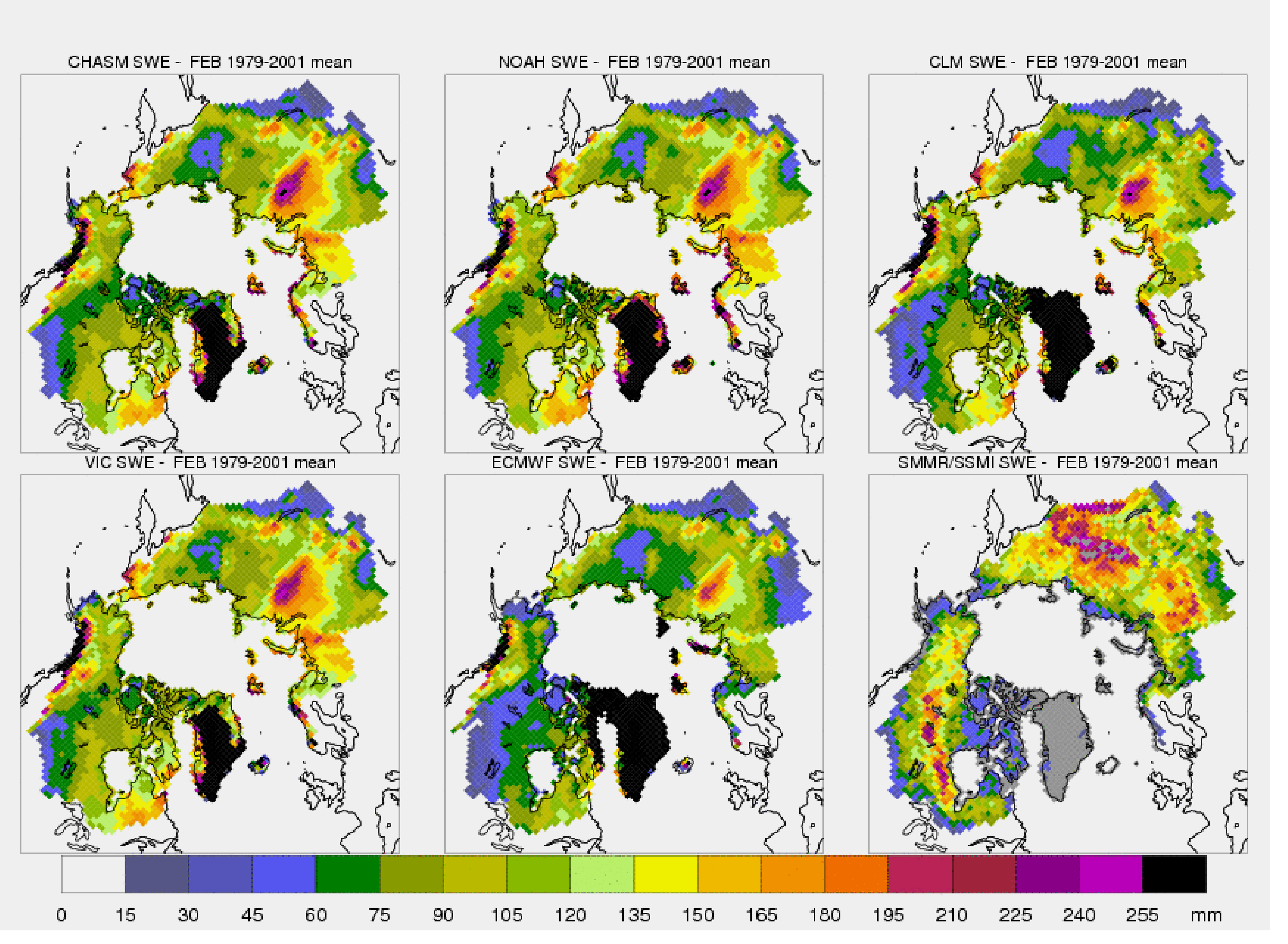
Comparisons of Observed and modelled snow depth at SnowMIP sites



Results for Changes in CLASS: SWE, density and snowpack depth

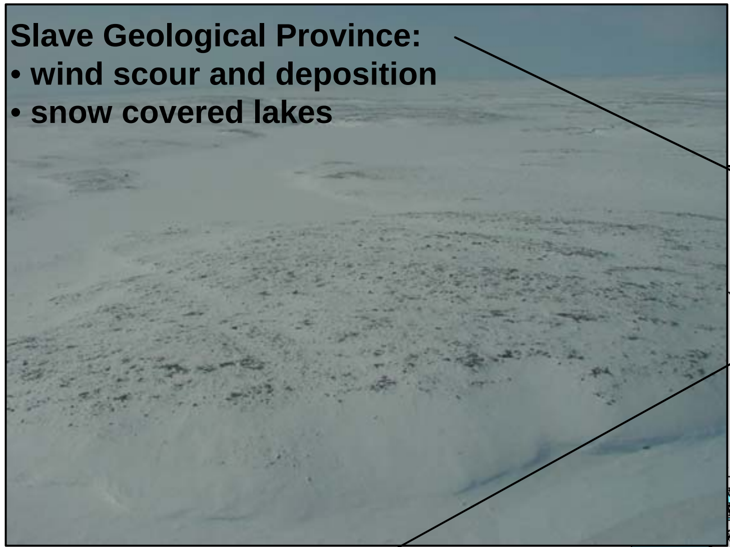


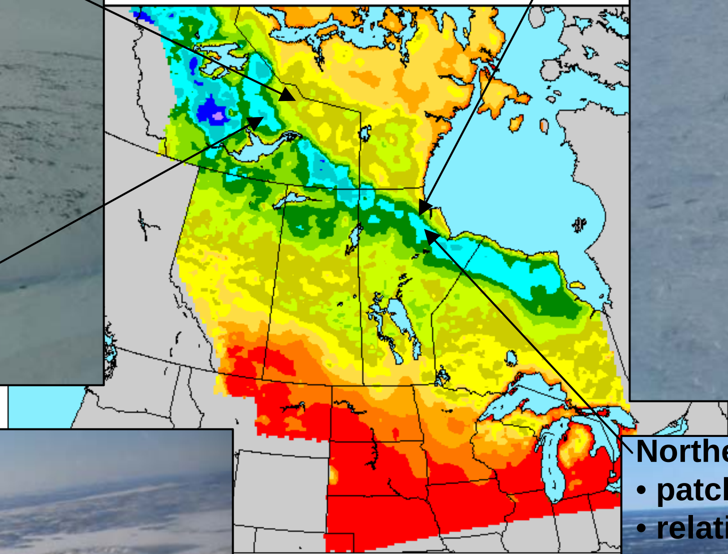
Snowpack storage from LSMs and SSM/I

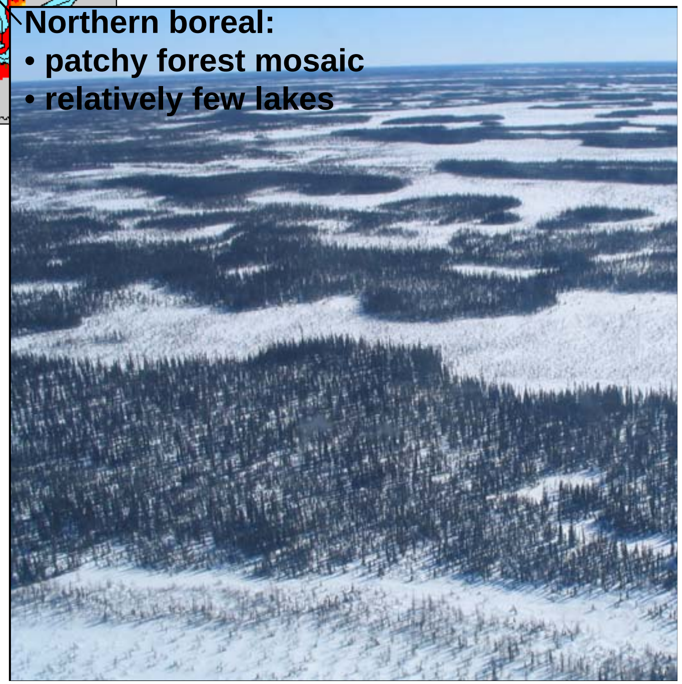


Courtesy, Mark Serreze, University Colorado

Do we know what we are really observing and modelling?

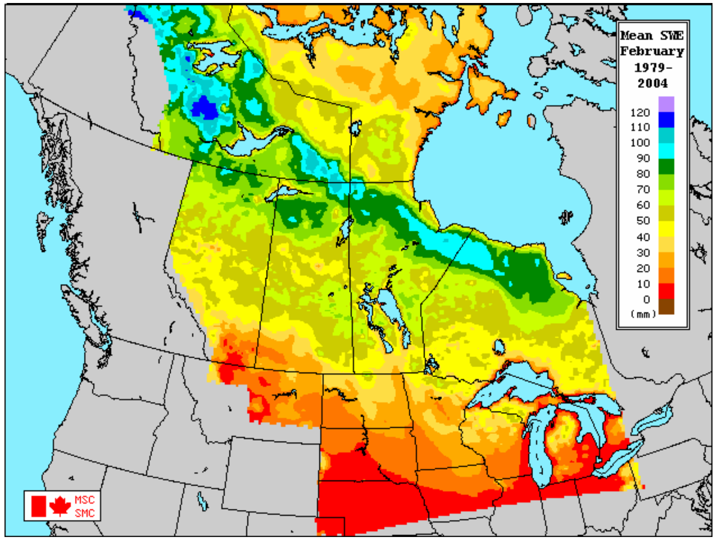






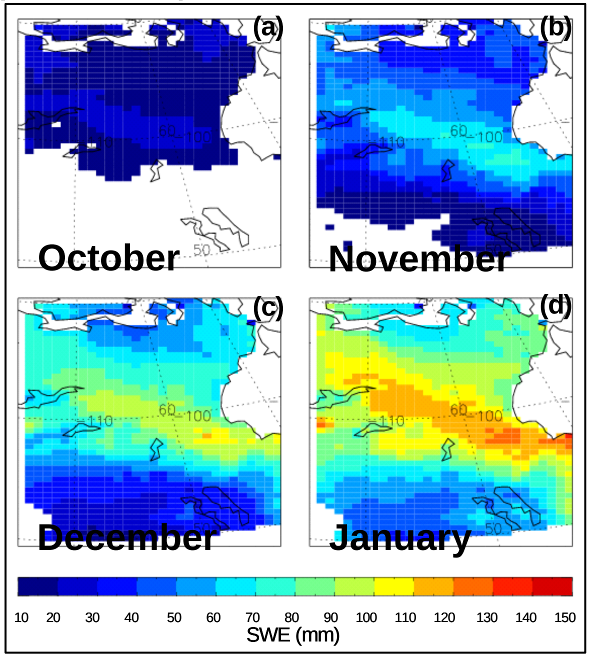
C. Derksen
Environment Canada

Snow – Observation and Modelling

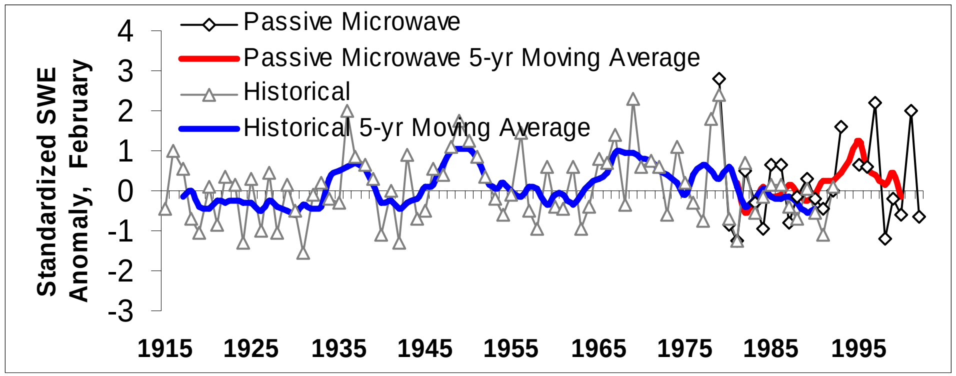


Expanded operational/research domain.

Ground and airborne evaluation campaigns.



Linkages with regional climate model simulations.



Long time series perspective by merging with conventional data record.

Principal Storm Tracks

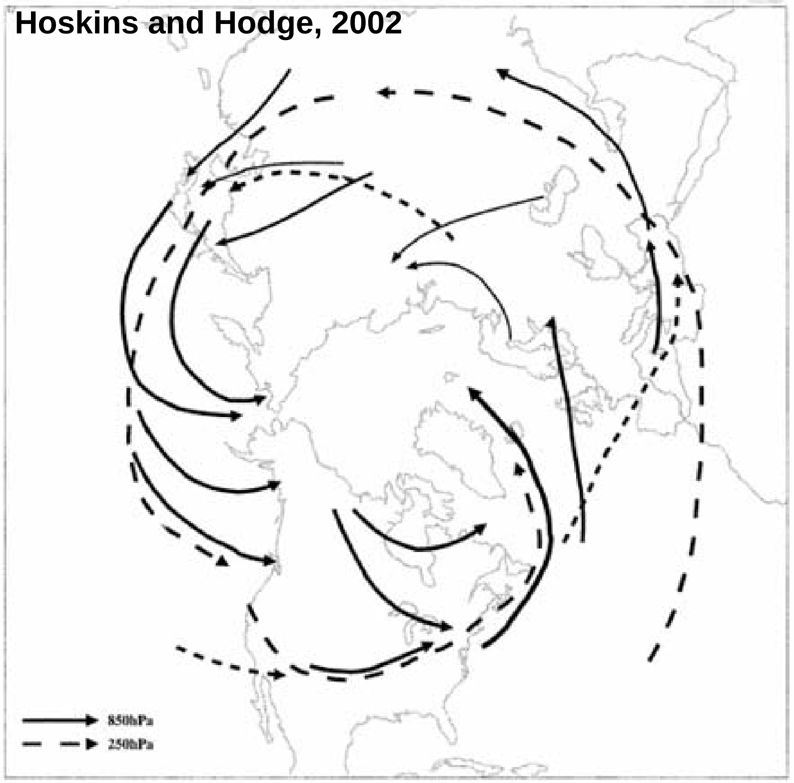
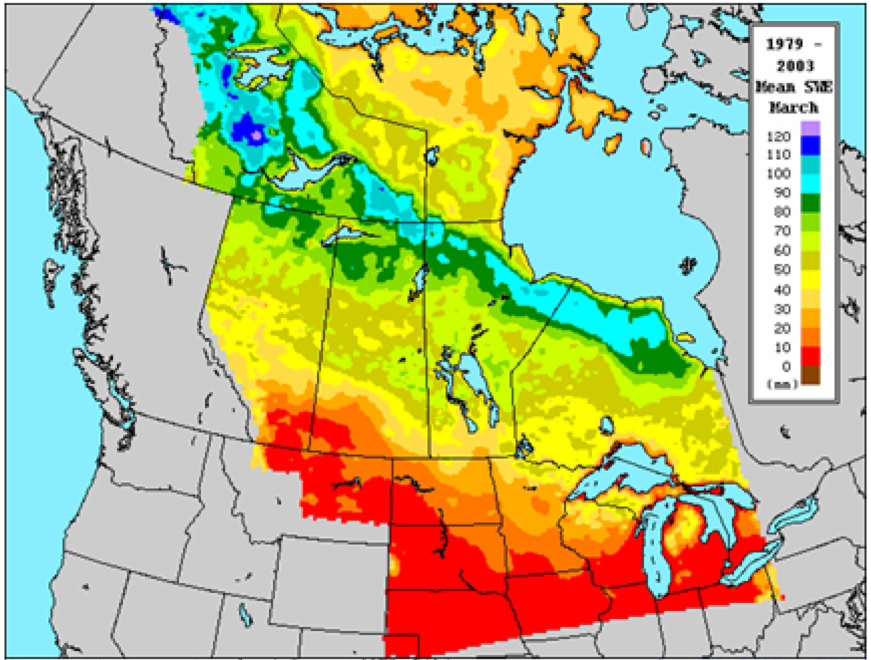
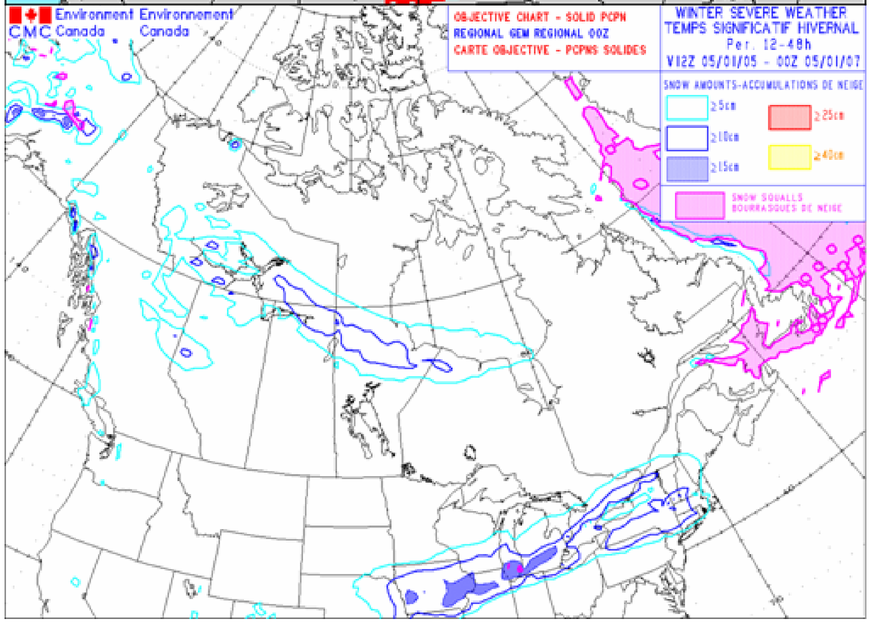


FIG. 14. Schematic of principal tracks for lower- (solid line) and upper- (dashed line) tropospheric storm track activity based on ξ_{850} and θ_{PV2}.

- ➢ Lower-tropospheric disturbances follow a preferred storm track over the northern boreal forest.

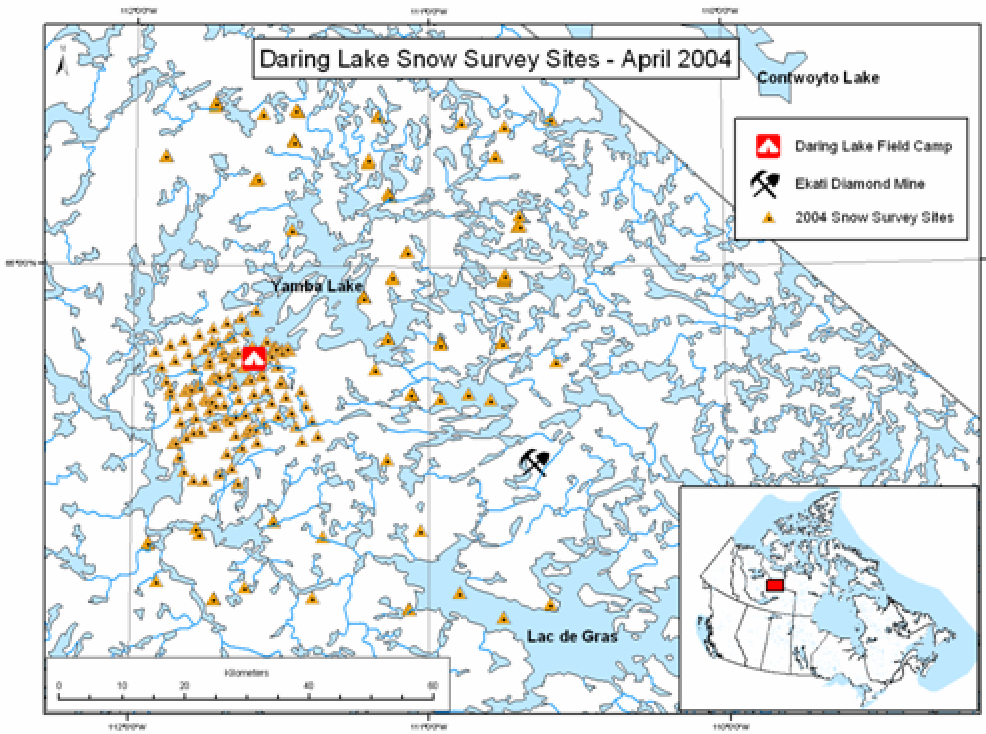
- ➢ CRCM experiments show weak boreal forest controls on frontogenesis and storm tracks, but the role of topography is significant.





CMC Severe Weather Forecast, January 5, 2005

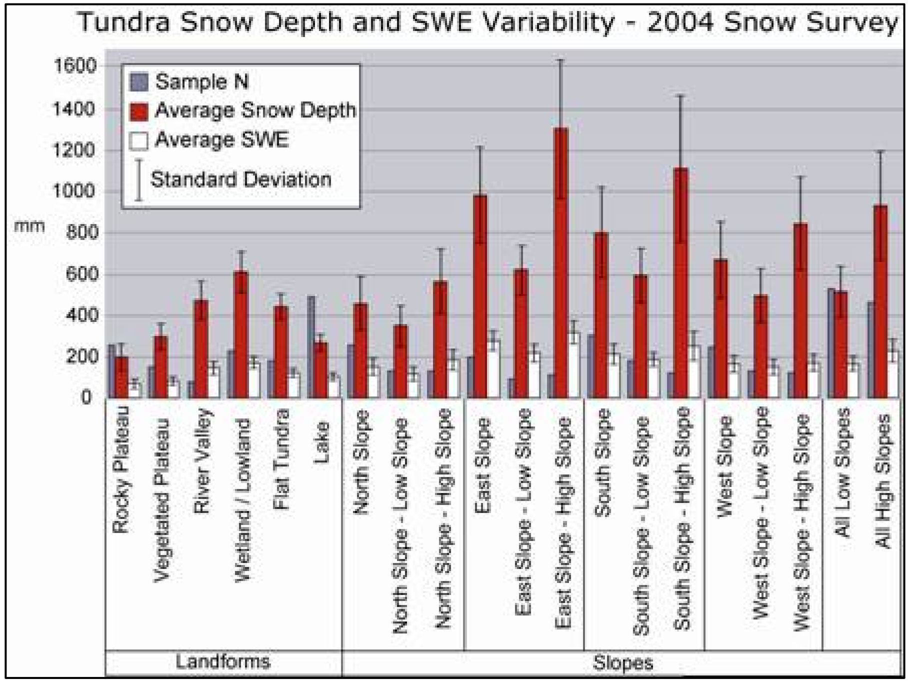
2004 Tundra Snow Survey Results

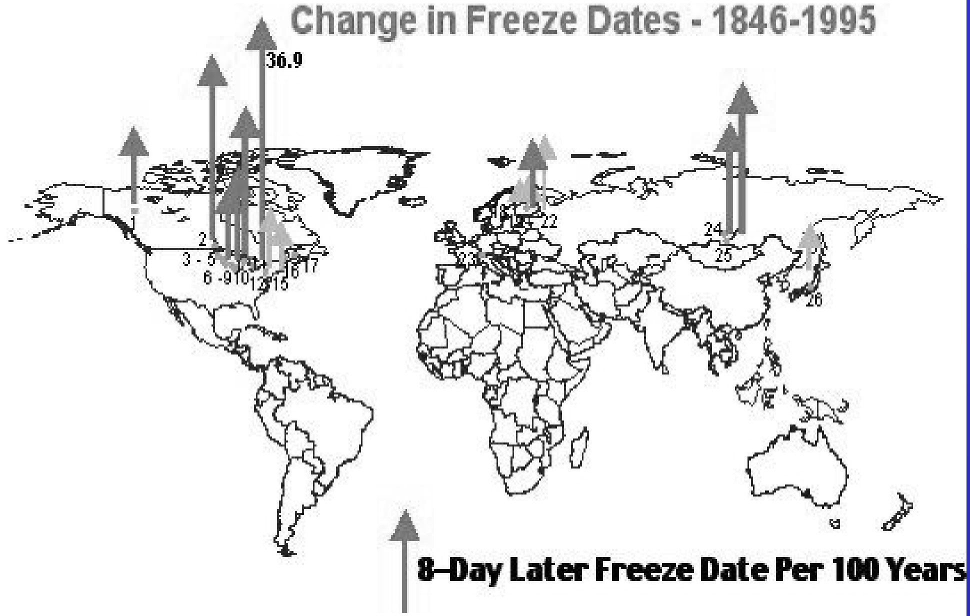


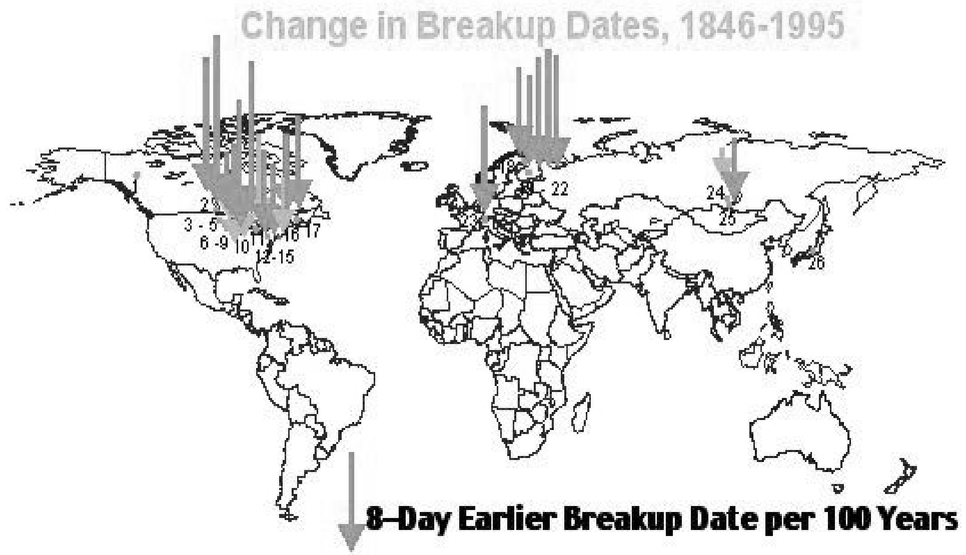
➢ Present passive microwave SWE retrievals (<100 mm) characterize SWE in open, wind-swept areas.

➢Challenges in this environment include:

- high snow density (up to 500 kg/m^3)
- high SWE in confined drift areas – slope and aspect are significant
- unresolved role of lake ice – fraction? ground-fast vs. floating?







HISTORICAL TRENDS IN RIVER-ICE EVENTS

analysis of global >100 year records found general shrinkage of ice season (from lake and a few river stations) by approximately 2 weeks/100 years

- **freeze-up 8 days later**
- **break-up 8 days earlier**

Magnuson et al. 2000 Science

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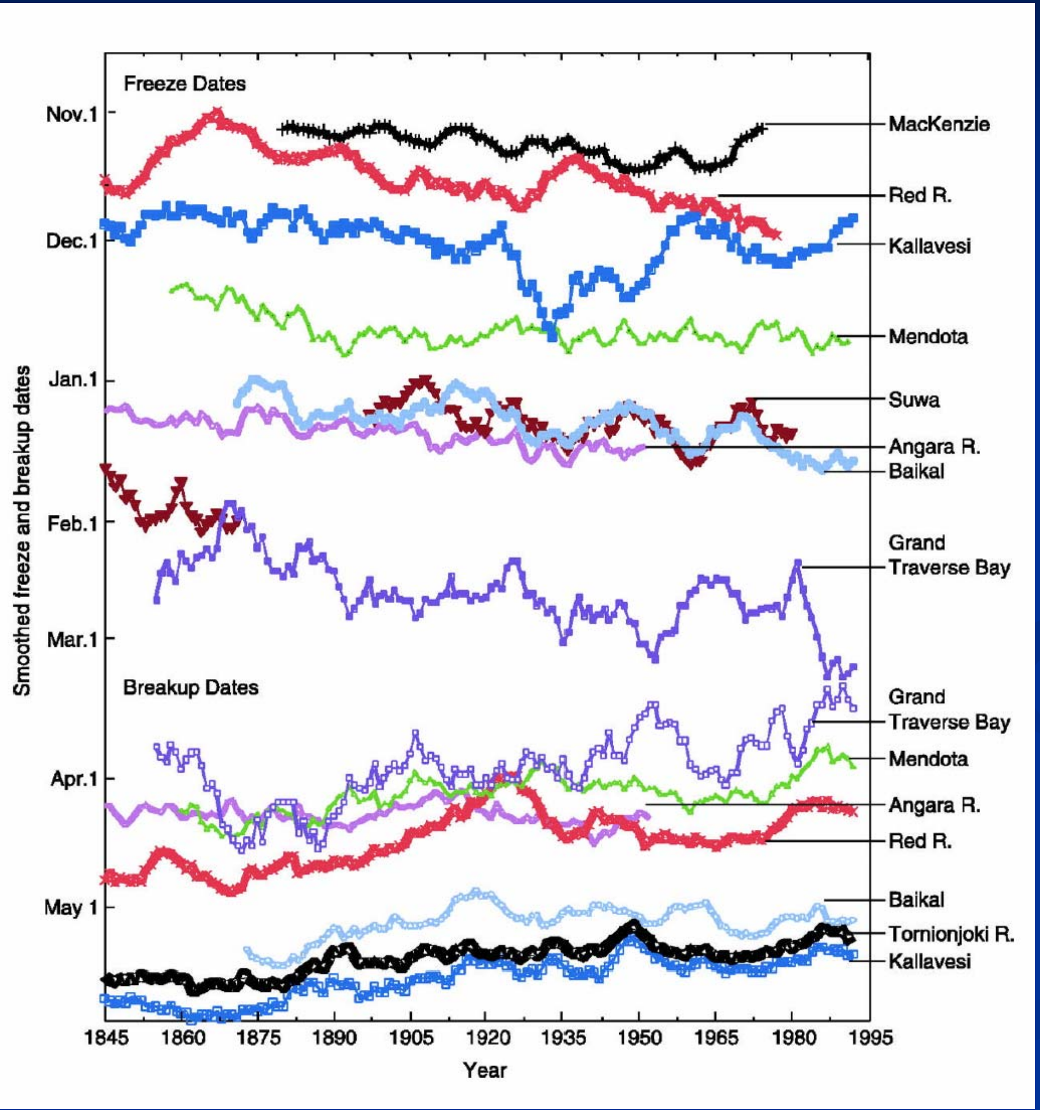
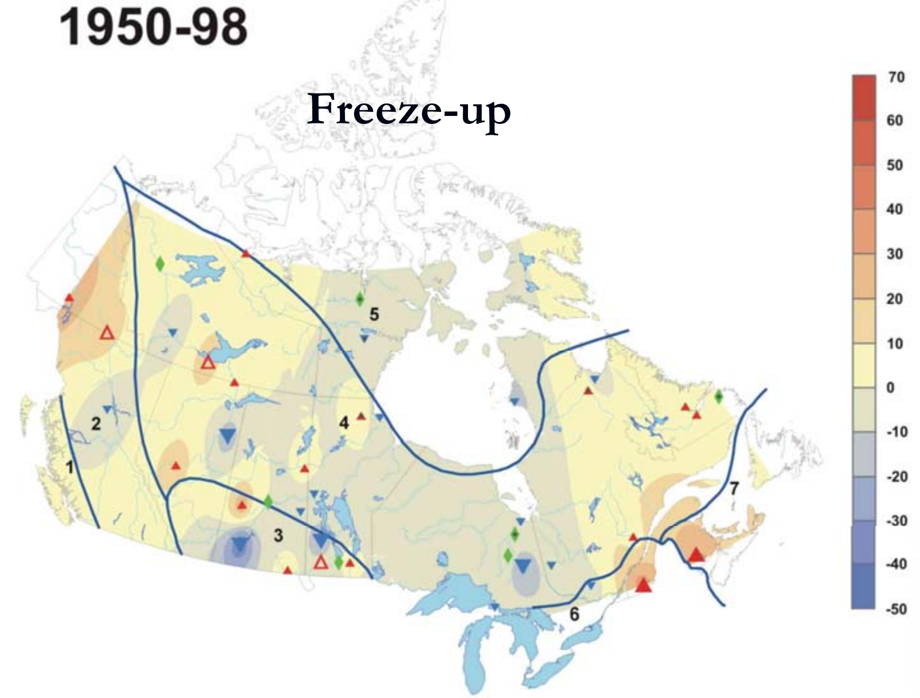
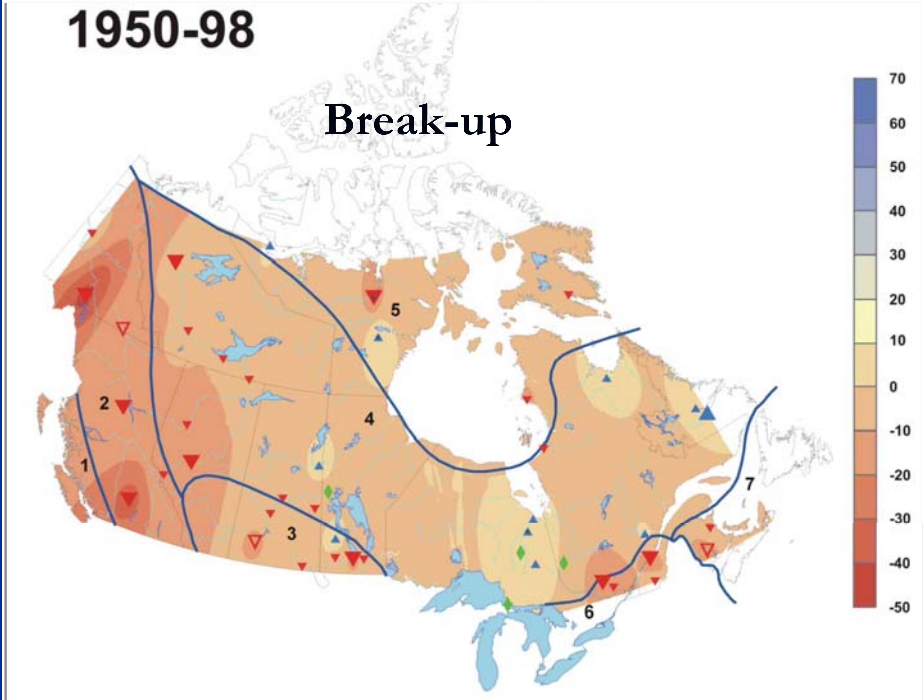
2. HISTORICAL TRENDS

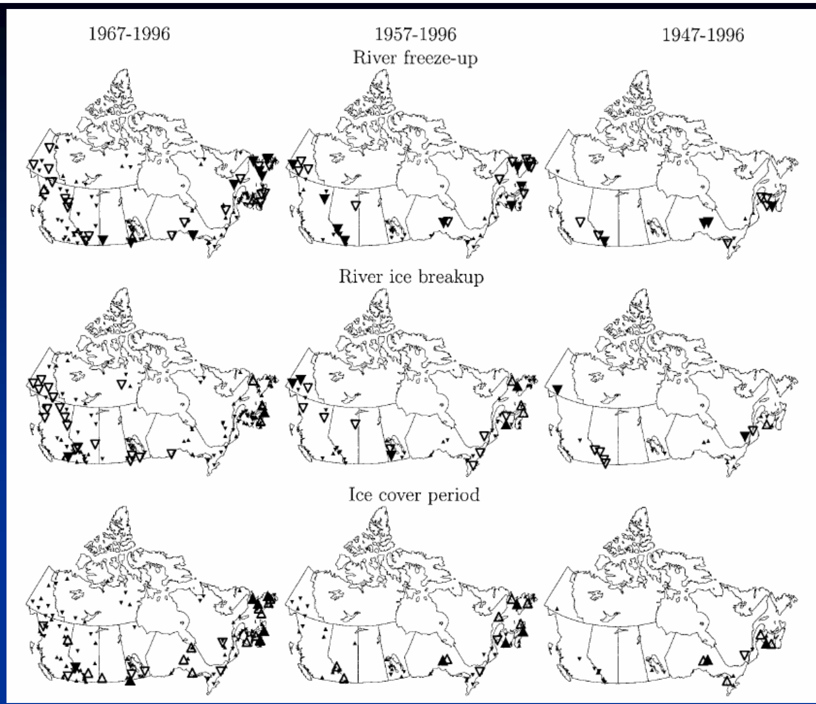


- **Global >100 year records**
- **Freeze-up delayed 5.7d/100yr**
- **Breakup = long-term advance of 6.3d/100yr ~ 1.2˚C/100yr**

from Magnuson et al. 2000

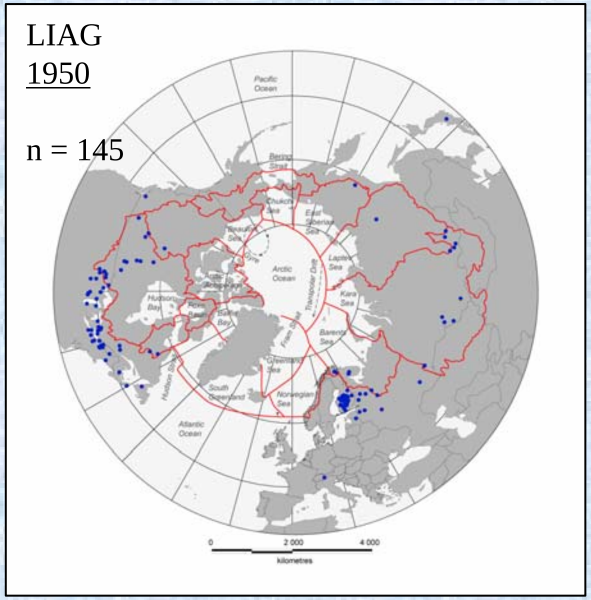


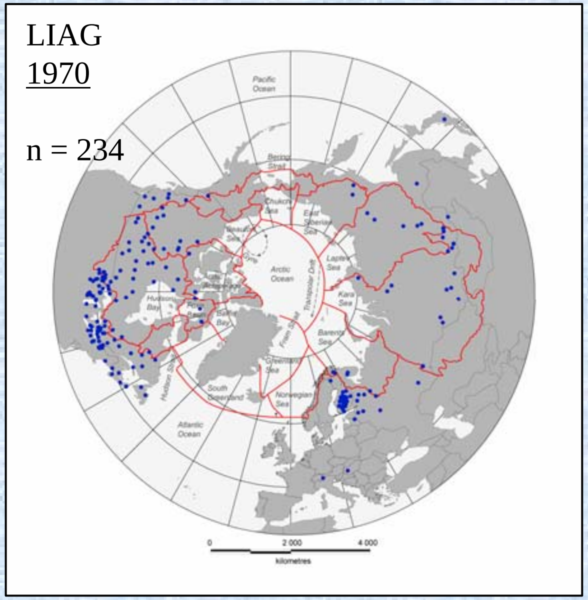


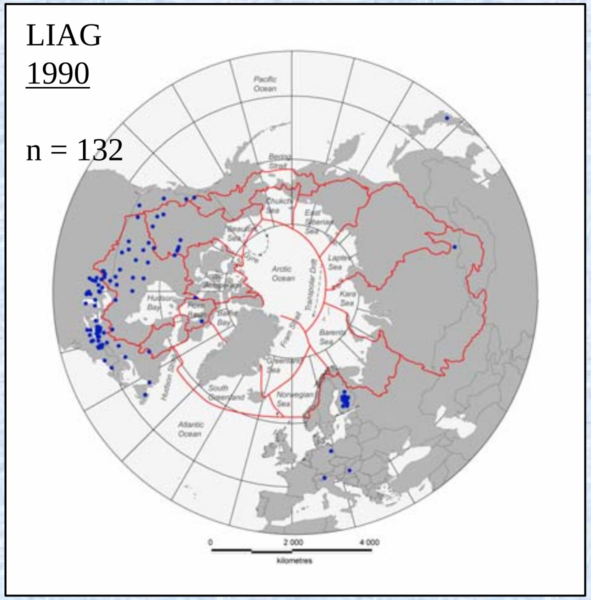


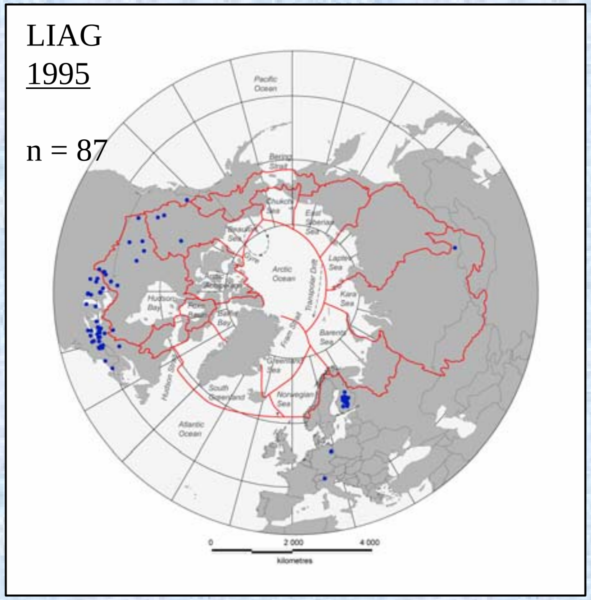
- **Over last ½ Century:**
  - **western Canada has significant trend towards earlier breakup**
  - **Eastern regions have little change or even small trends toward later breakup**
  - **freeze-up spatially complex with no discernible trends**

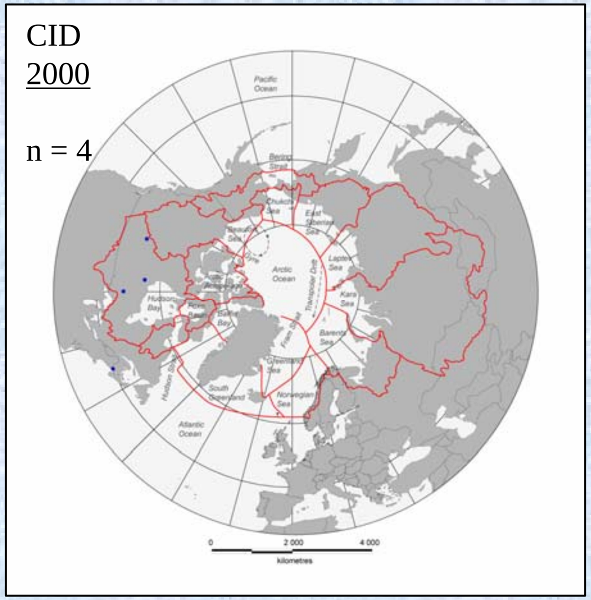
From Zhang et al. 2001; Lacroix et al. 2005









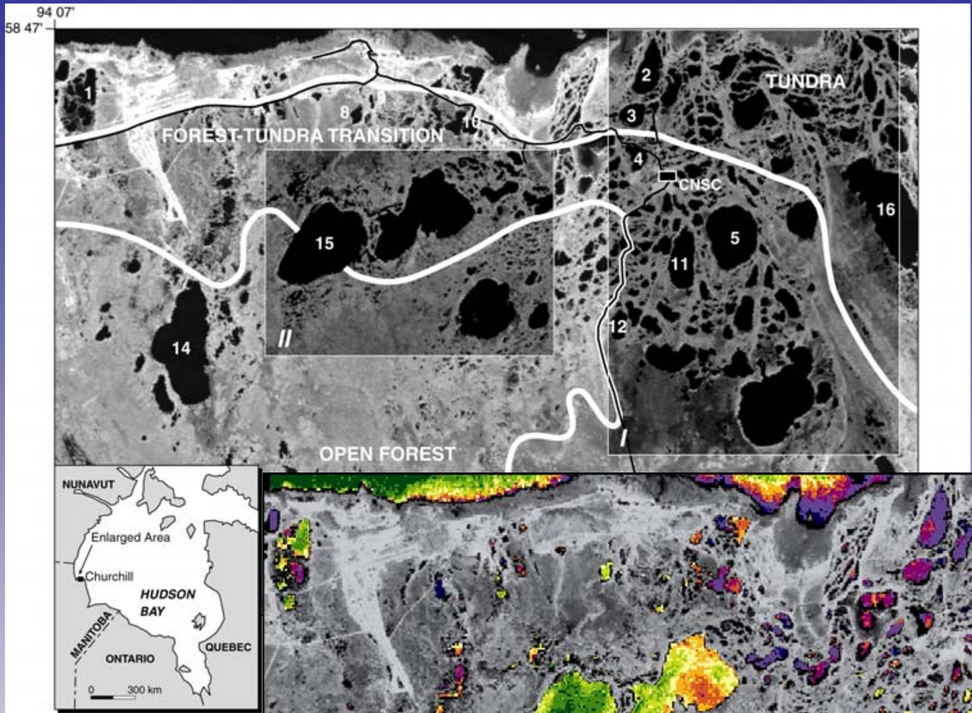


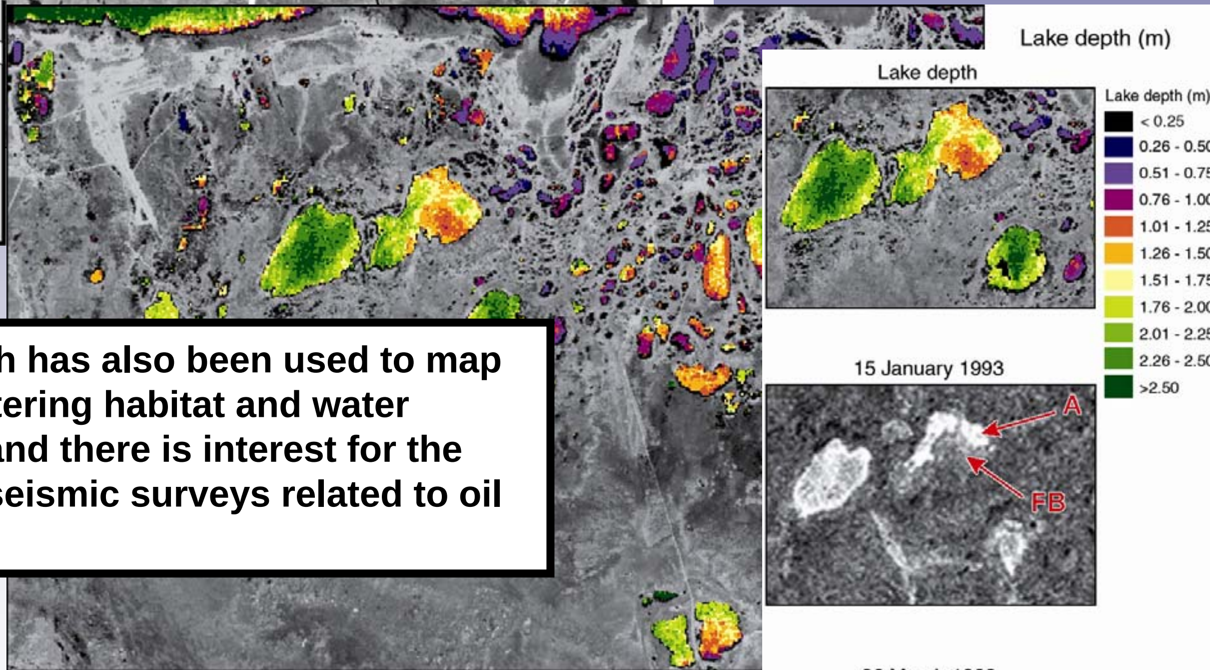
Lake Ice Data Base

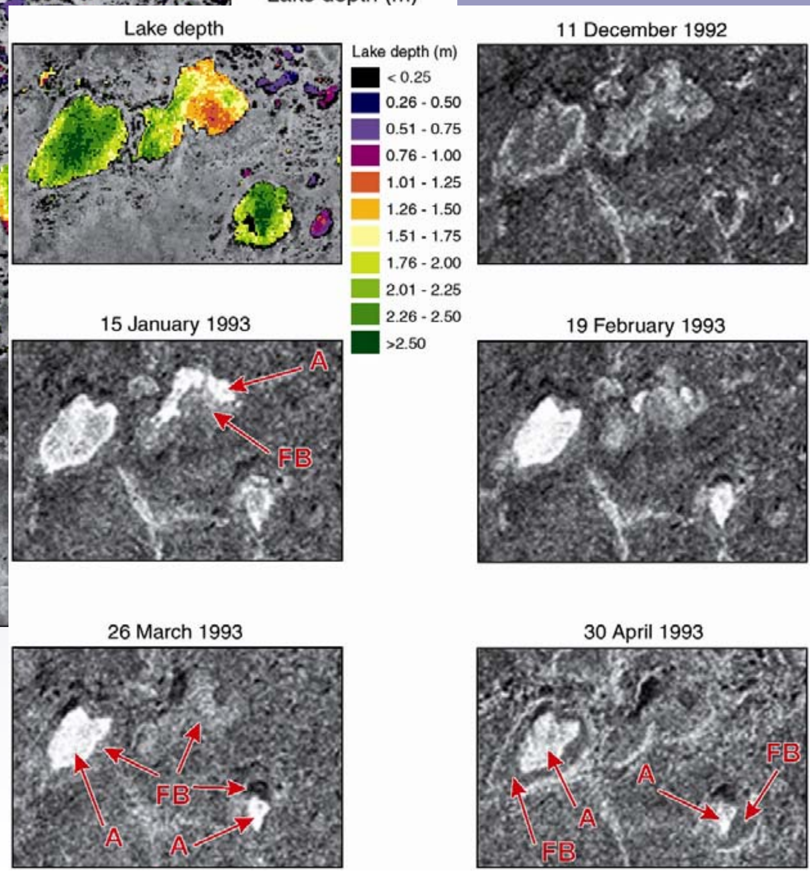
Courtesy C. Duguay

Workshop on Atmospheric Reanalysis, Apr 2006. Identified the need for better sea ice data in the pre-satellite era, data on lake ice

Determination of lake depth and ice thickness in the Hudson Bay Lowland using ERS SAR and Landsat TM data







The approach has also been used to map fish overwintering habitat and water availability, and there is interest for the planning of seismic surveys related to oil exploration.

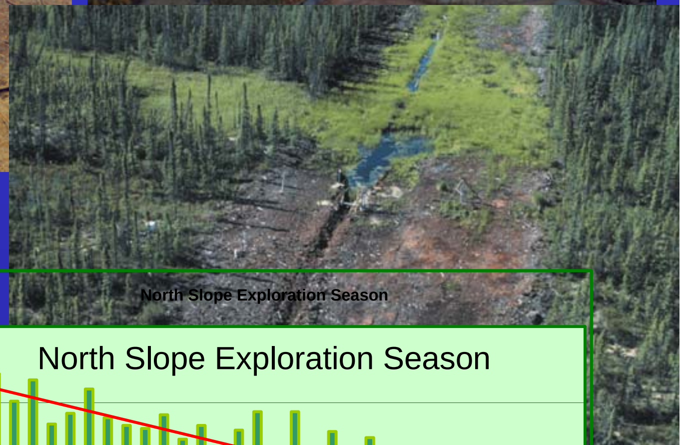
<u>Reference</u>: Duguay, C.R. and P.M. Lafleur, 2003. . Estimating depth and ice thickness of shallow subarctic lakes using spaceborne optical and SAR data. *International Journal of Remote Sensing*, 24: 475-489.

Warming and thawing of frozen ground can lead to instabilities in the landscape

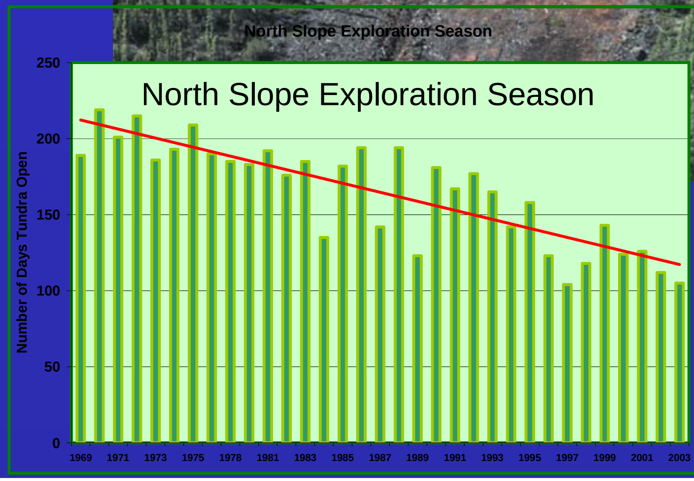
Unstable ground

Active layer detachment

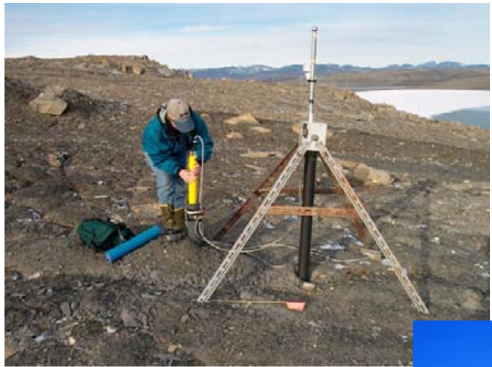
Thawing of ground ice and thermokarst terrain

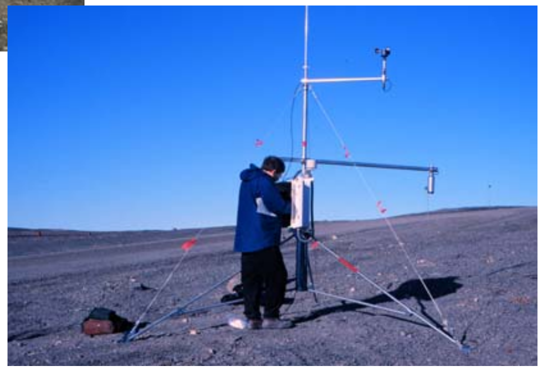


Damage to buildings and infrastructure

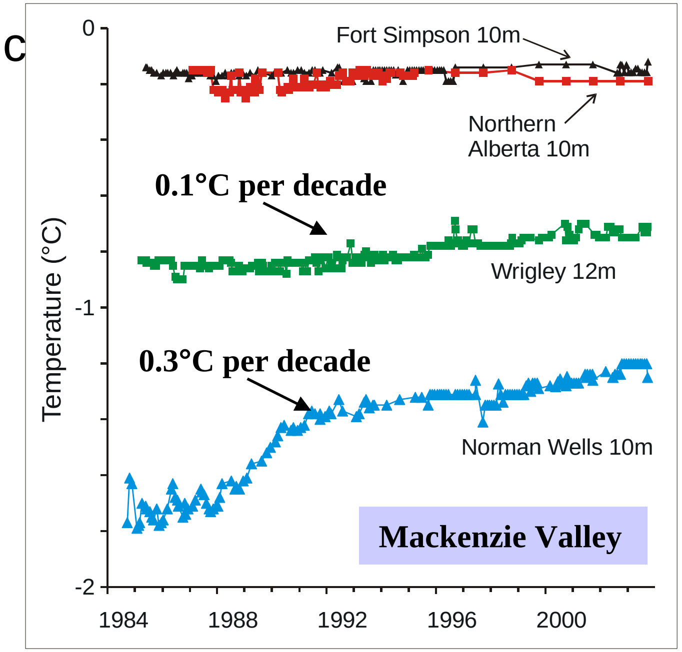


Trends in Permafrost Temperature across the Canadian Arctic

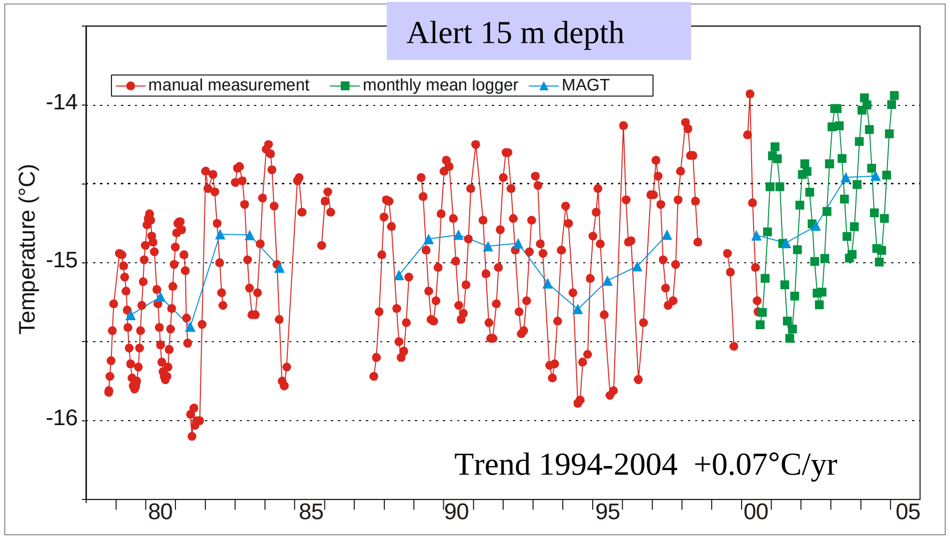




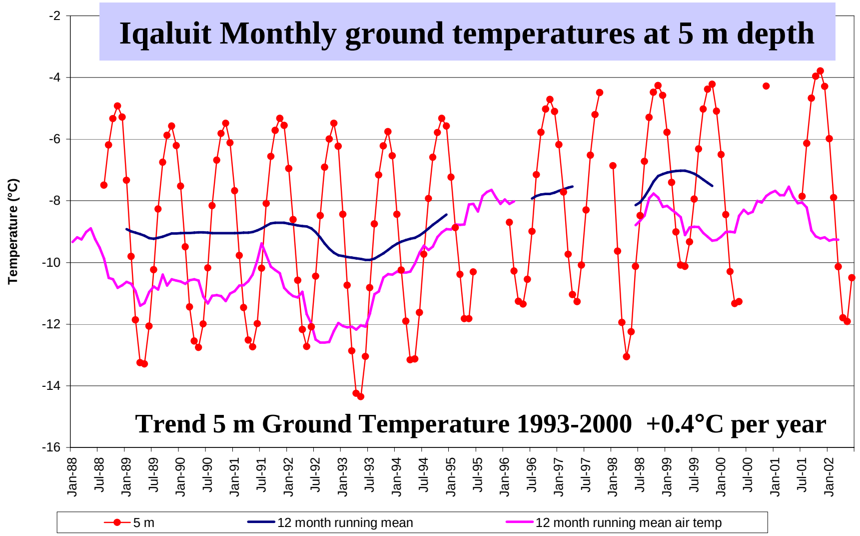
Western Arctic



High Arctic



Eastern Arctic



Vulnerabilities of the Permafrost-Carbon-Climate System

Research and Assessment Components

1. Spatial Distribution of Frozen Ground*

Current spatial distribution of frozen ground.

2. Carbon Stocks

Current soil carbon content in frozen soils

3. Carbon Fluxes*

Current Carbon Fluxes in an out of frozen soils

4. Carbon Dynamics

Processes controlling carbon dynamics in thawing frozen soils (biogeochemical modeling and experimention including flux towers)

5. Permafrost Dynamics*

Permafrost dynamics (thawing) under warming (land surface models or permafrost modeling including hydrological processes)

6. Vegetation Dynamics

Vegetation replacement as permafrost thaw and associated C dynamics

7. Climate Impacts*

Effects of permafrost C emissions on climate

Vulnerabilities of Permafrost-Carbon-Climate system

400 Pg C

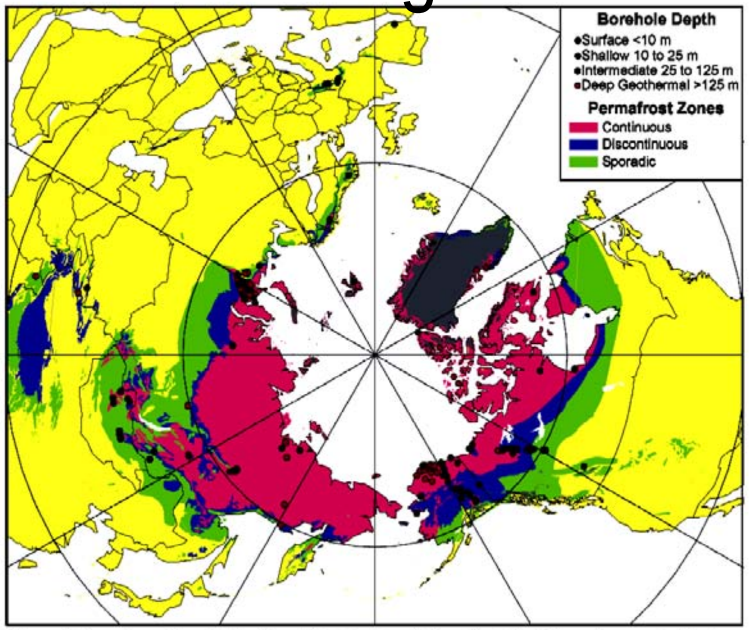


Figure 2. Location of boreholes for which site descriptions (metadata) have been submitted (compiled by S. Smith, Geological Survey of Canada, July 2003).
Global Terrestrial Network for Permafrost(GTN-P). IPA

Anthropogenic
C emissions

↓ **(+)**

Warming

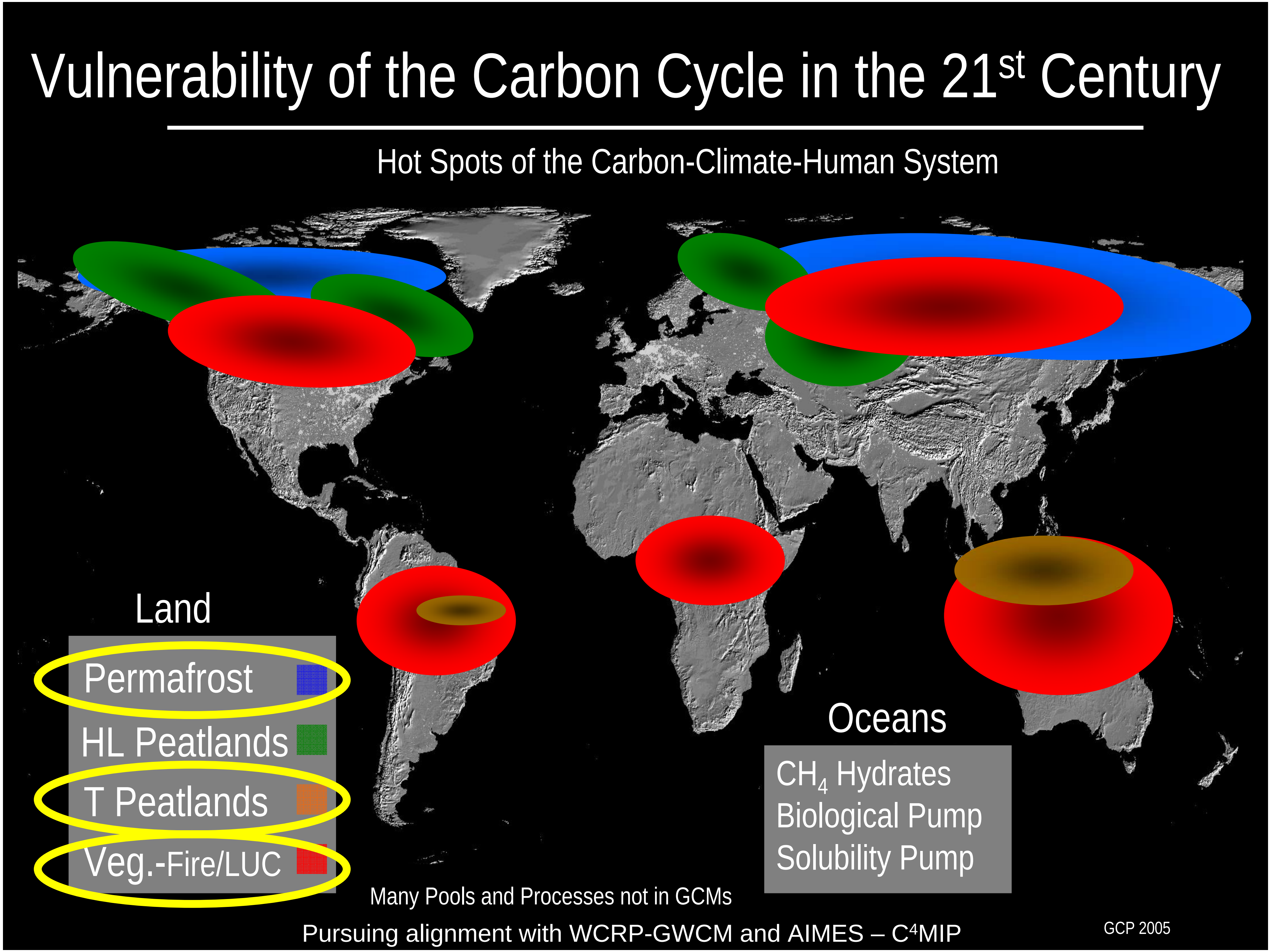
↓ **(+)**

Permafrost

↓ **(+)**

C emissions/sinks?

(+)


Vulnerability of the Carbon Cycle in the 21st Century
Hot Spots of the Carbon-Climate-Human System
Land
Permafrost
HL Peatlands
T Peatlands
Veg.-Fire/LUC
Oceans
CH4 Hydrates
Biological Pump
Solubility Pump
Many Pools and Processes not in GCMs
Pursuing alignment with WCRP-GWCM and AIMES – C4MIP
GCP 2005

Research Synthesis: Permafrost Carbon and Feedbacks

Global Carbon Project (GCP)
Climate and Cryosphere (CliC-WCRP)
International Permafrost Association (IPA)
Contribution to AIMS in the future

Distribution of Permafrost and C stocks

- Spatial distribution – digital database
- Southern boundary - changes in the next 100 years
- Soil carbon content (including below 1-2 m depth)

Carbon Processes in thawing permafrost

- Biogeochemical modeling of C dynamics in thawing permafrost:
  - Controls of carbon emissions in thawing permafrost
  - Development of algorithms for complex models
  - Future trajectories of carbon emissions

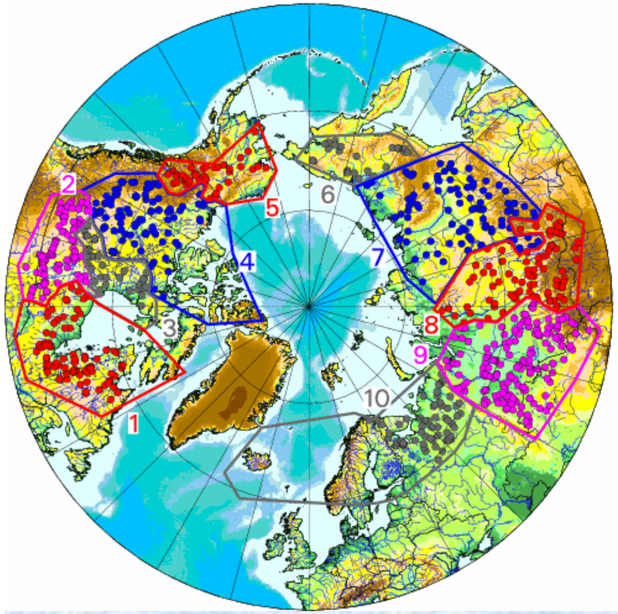
Carbon feedbacks to Climate

- Off-line calculations of carbon emissions impacts on climate change.
- Earth System models, including permafrost models, to bring critical elements of permafrost dynamics, hydrological, and carbon cycle components to their model development.

Workshop Series 2005-07

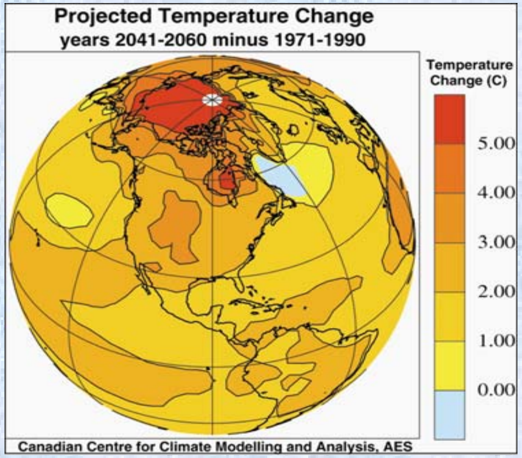
Funded by:
European Science Foundation;
National Center for Ecological Analysis and Synthesis (NCEAS-NSF);
ICSU grant to IGBP

PEACE - PErmafrost and Carbon Emissions (IPY 2007-08)



Arctic HYDRA

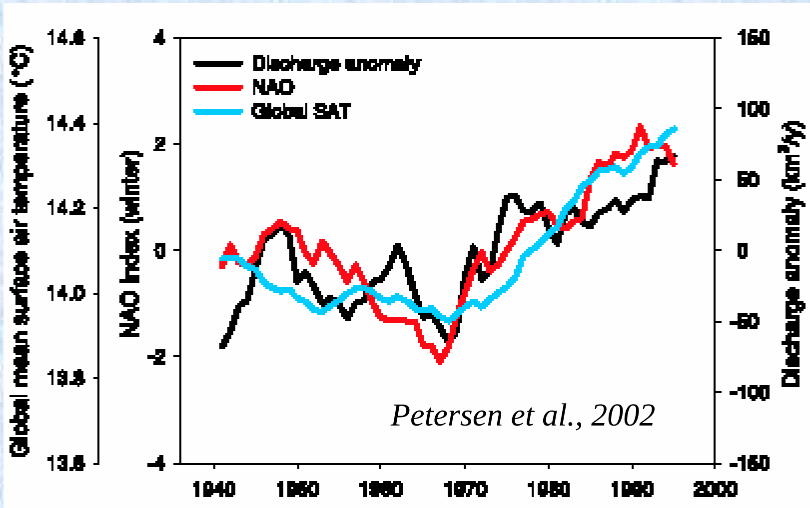
The Arctic Hydrological Cycle Monitoring, Modelling and Assessment Program



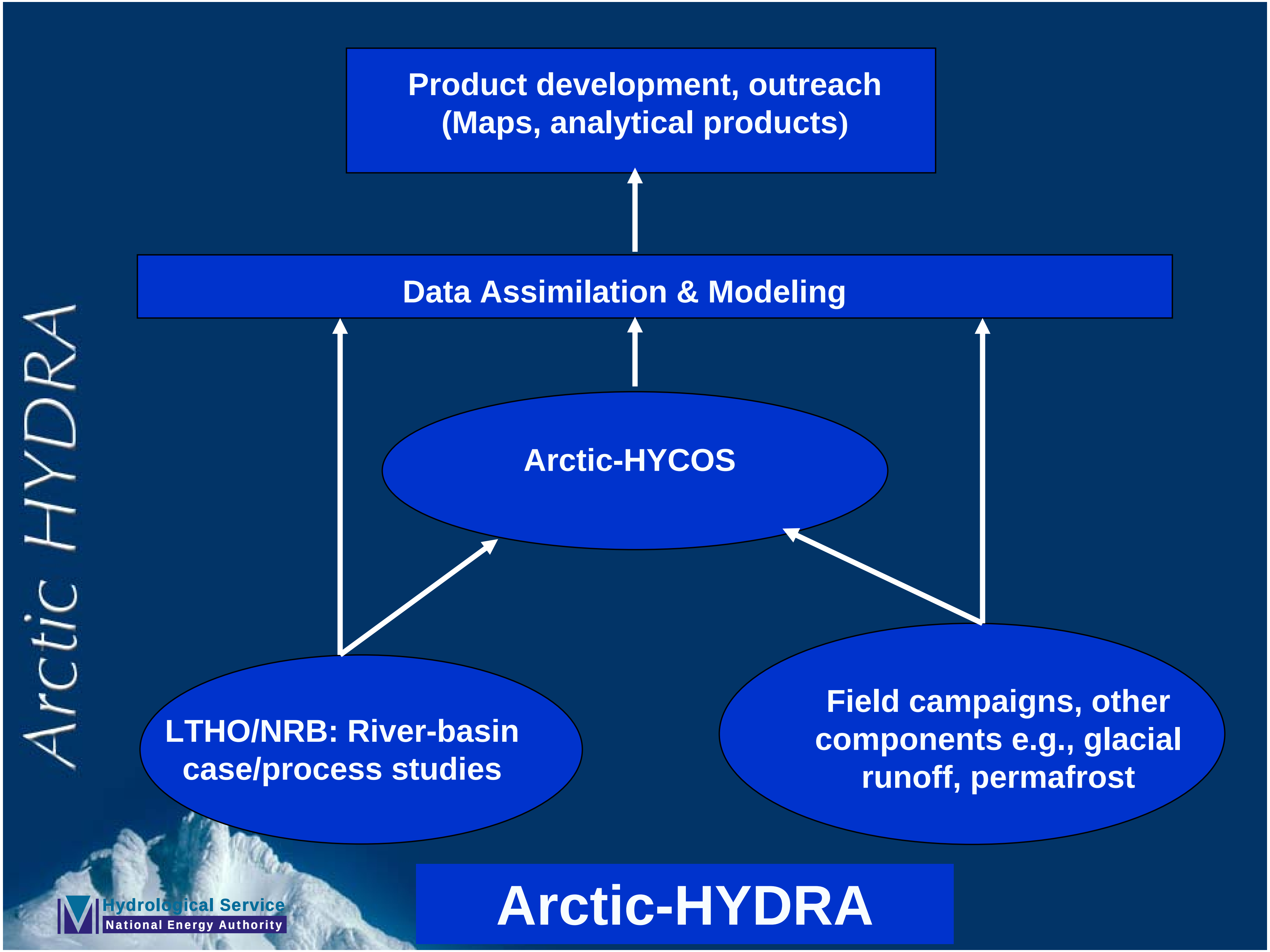
Boer et al. (1999)

- *Polar amplification of warming:*

- *Observed trends:*



The hydrological cycle of the polar regions is one of the biggest unknowns, but is also one of the most crucial triggers in the global climate system

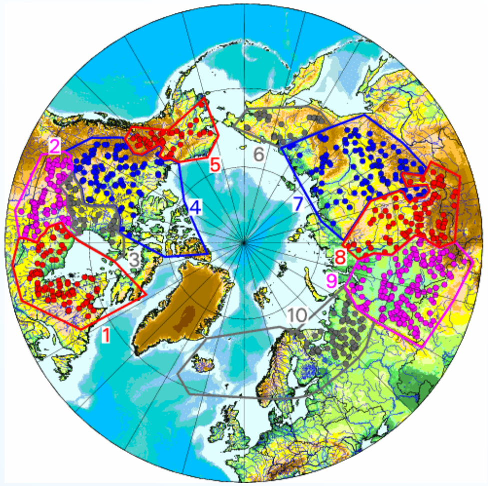

Product development, outreach
(Maps, analytical products)
Data Assimilation & Modeling
Arctic-HYCOS
LTHO/NRB: River-basin case/process studies
Field campaigns, other components e.g., glacial runoff, permafrost
Arctic HYDRA
Hydrological Service
National Energy Authority
Arctic-HYDRA

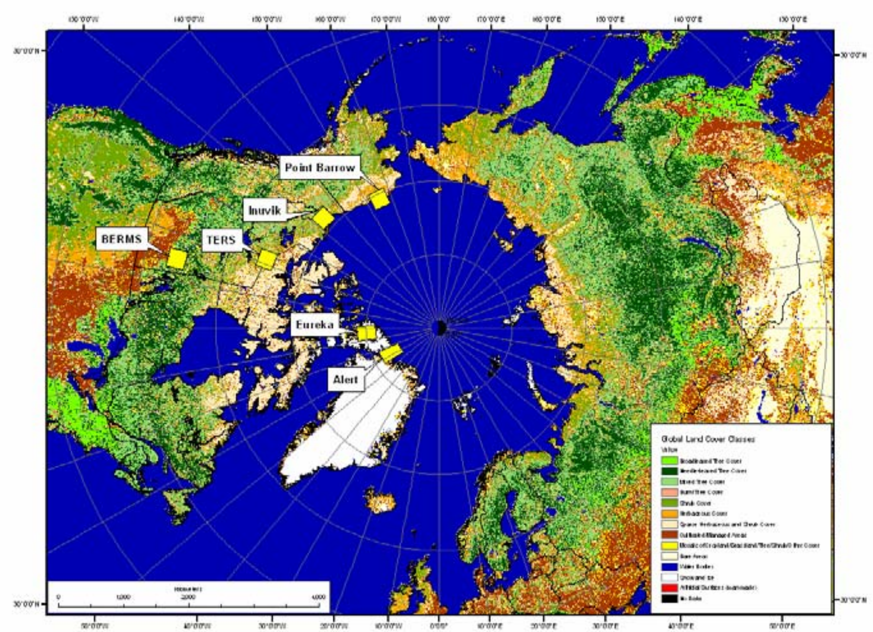
High Latitude Super Sites

Enhanced observing systems

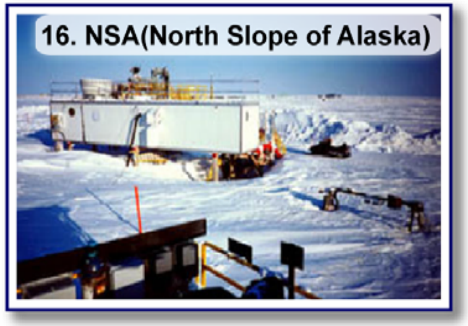
- **Reference climate stations (GCOS)**
- **Hydrometric**
- **Cryosphere - in-situ and remote sensing**
- **Ship-board upper-air**
- **Ozonesondes**
- **Alert/Eureka – SEARCH, PEARL**
- **Barrow, Tiksi?**
- **Multi-disciplinary observatories – atmosphere, cryosphere, ecosystem, flux**
- **COMAAR, CEON**
- **Arctic coastal dynamics**
- **Data access and management**

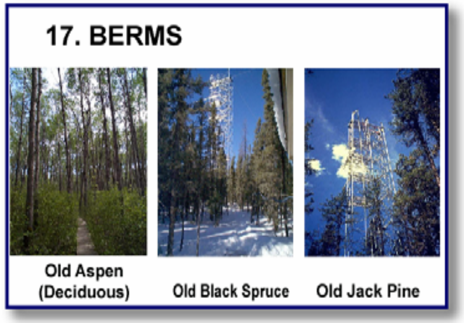
Ability to apply global and regional climate model to Arctic issues

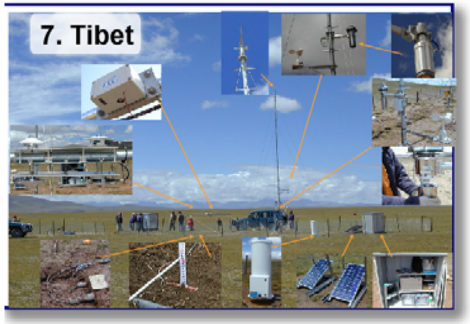


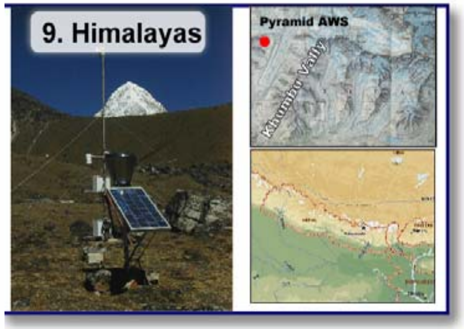


Source: The Global Land Cover Map for the Year 2000, 2003. GLC2000 database, European Commision Joint Research Centre. http://www-gvm.jrc.it/glc2000. (Regrouped 23 original classes into 14 : Peter Toose, MSC)



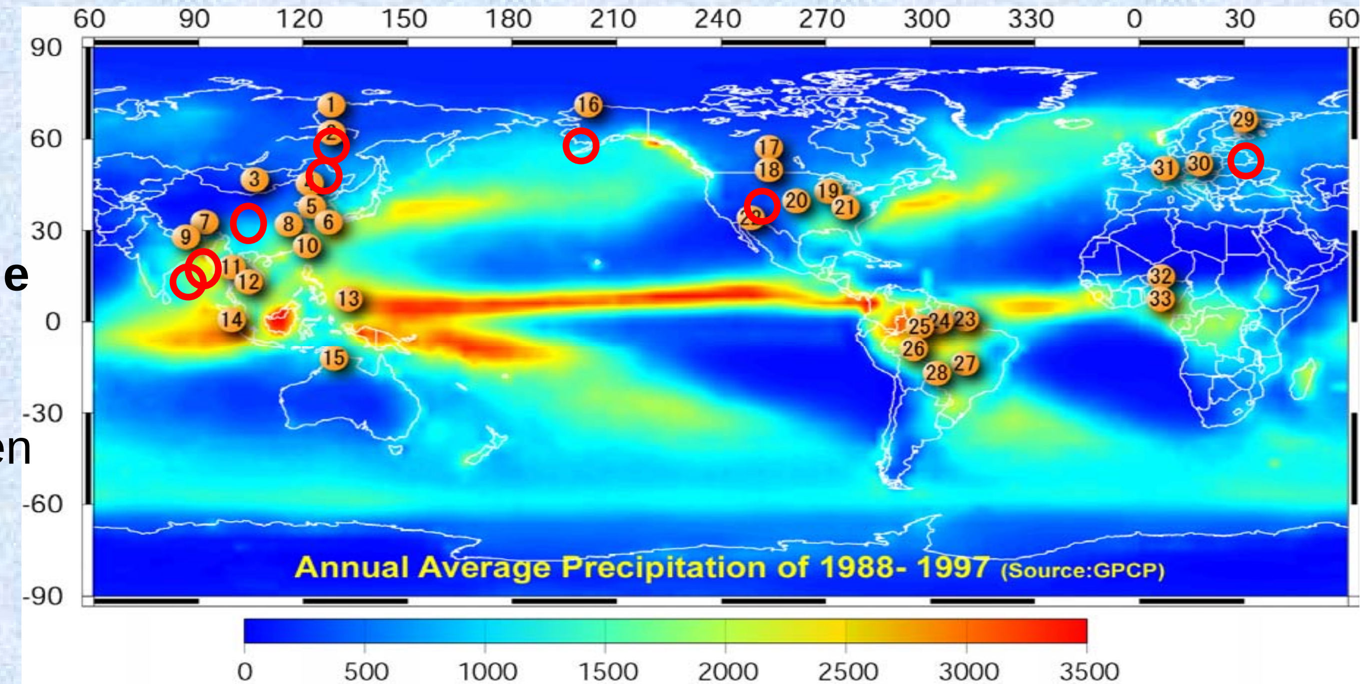




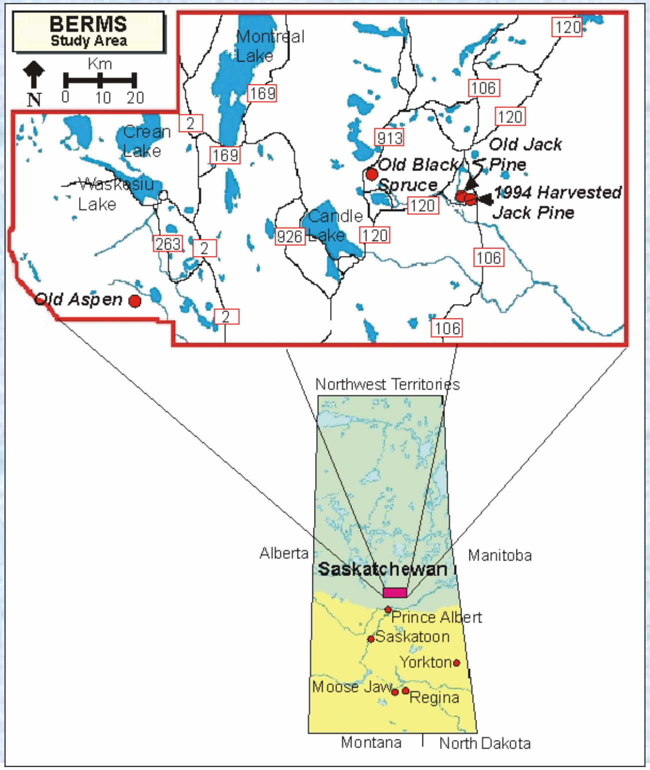


CEOP Reference Site in the Cold Regions

water/energy cycle in the cold region:
solid precipitation, snow cover, soil moisture, frozen ground, vegetation….

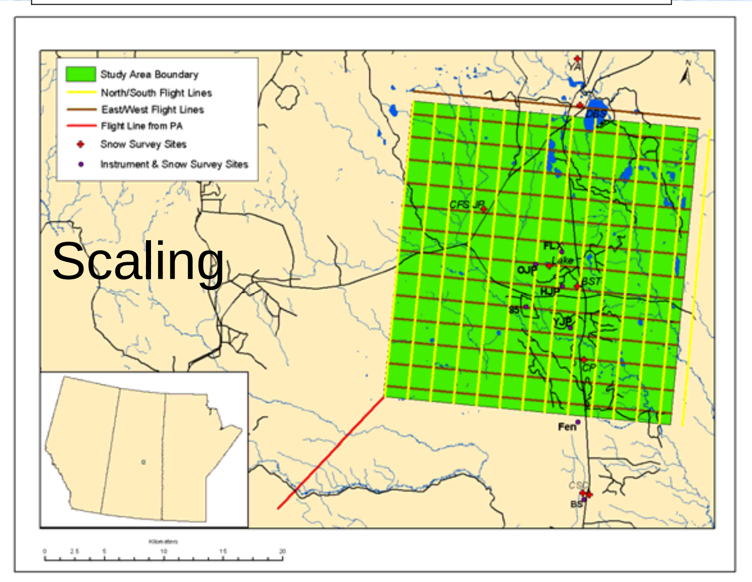


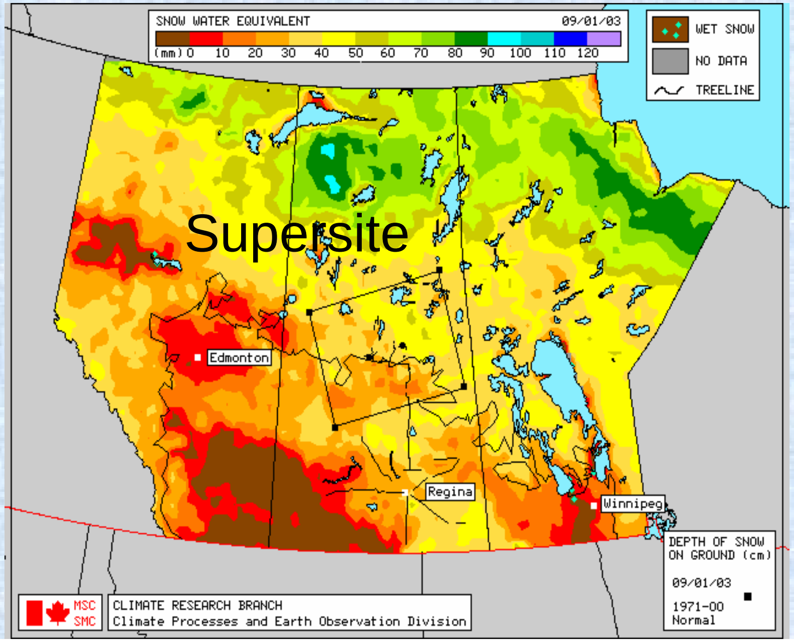
Integrated Studies, Joint Projects



Supersites

- *Produce baseline terrestrial cryosphere products for model validation and climatological assessment*

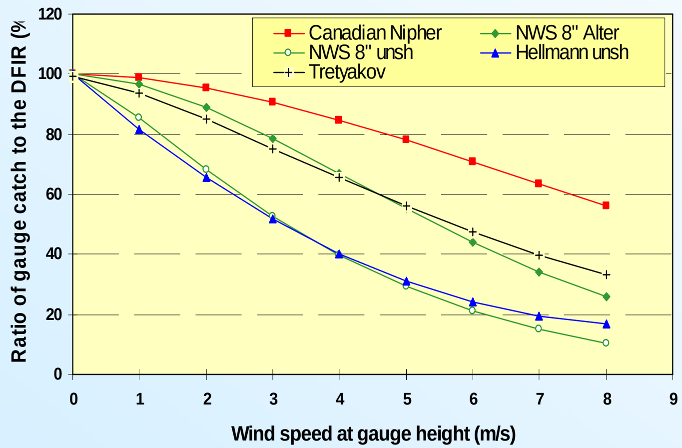




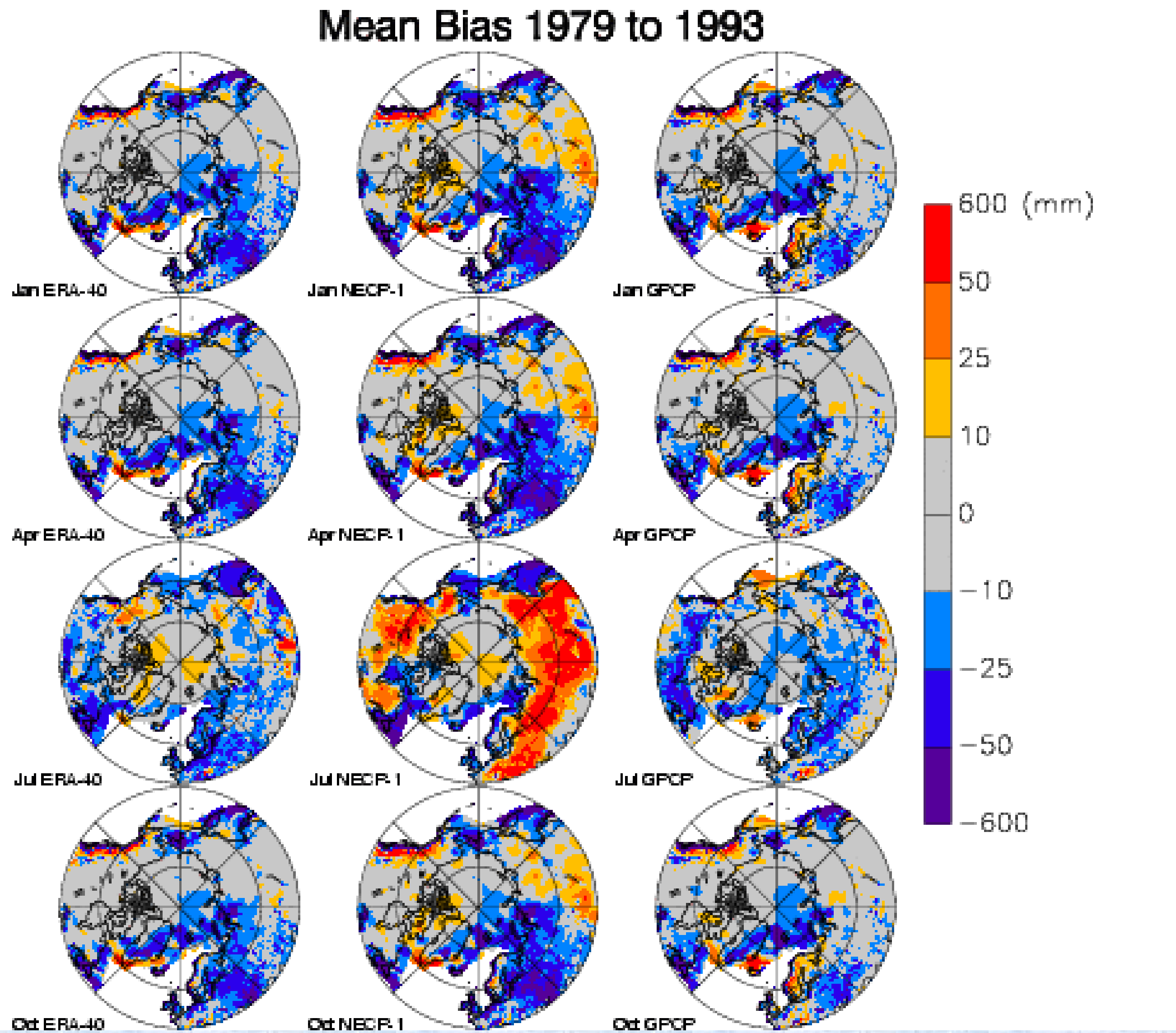
Quantification of Cold Region Precipitation (D.Yang, rapporteur)

- *CliC will work with GPCC and GPCP on the development of data sets, adjusted for known systematic errors, suitable for hydrological and climate modelling*
- *through IGOS-P and with others (GCOS), update observing procedures and standards for cryospheric variables*
- *Development and assessment of new technologies for precipitation measurement in cold climate regions is essential – IPWG, WCRP*
- *CliC focus on Precip in Cold Regions – strong link with GPCC*
- *GPM - Ground Validation in high latitudes*
- *What can we do for determining precipitation in polar regions for the IPY (March 1 2007-March 1 2009)?*
- *What do modellers need to validate precipitation in cold climates?*

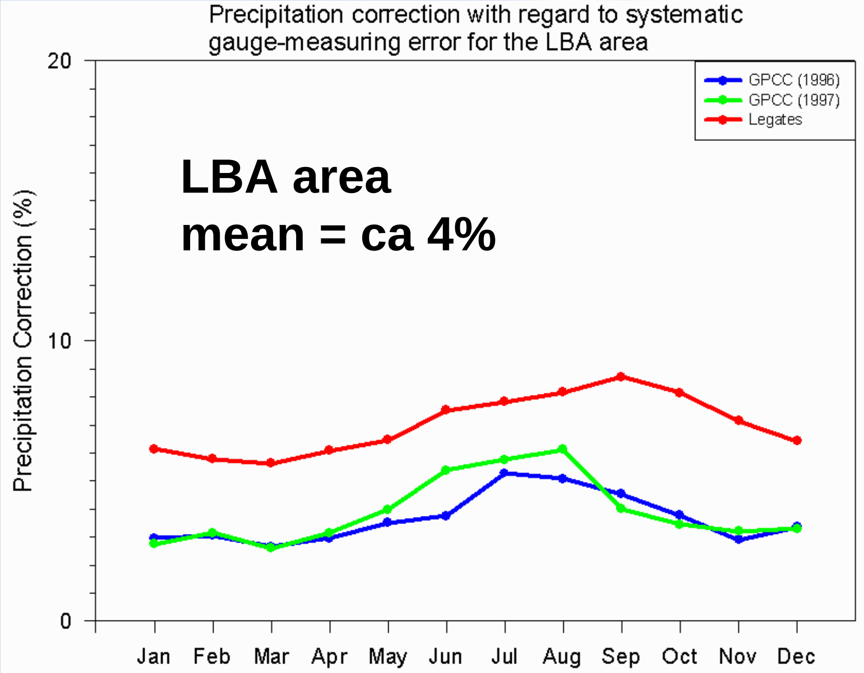
Impact of automation

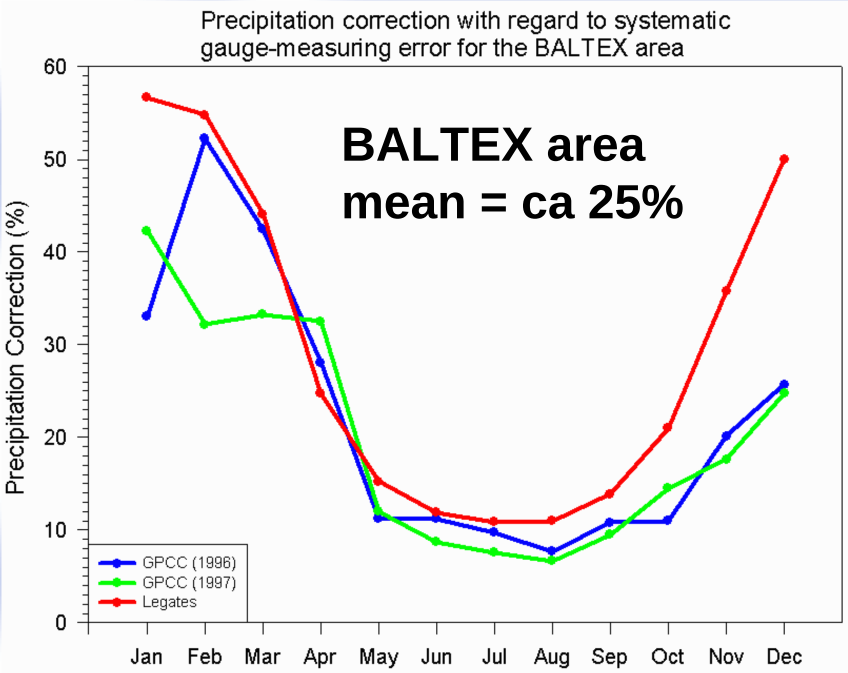


Precipitation Biases: ERA-40, NCEP-1 and GPCP



Mean percentual correction for all SYNOP precipitation based on GPCC‘s new correction method

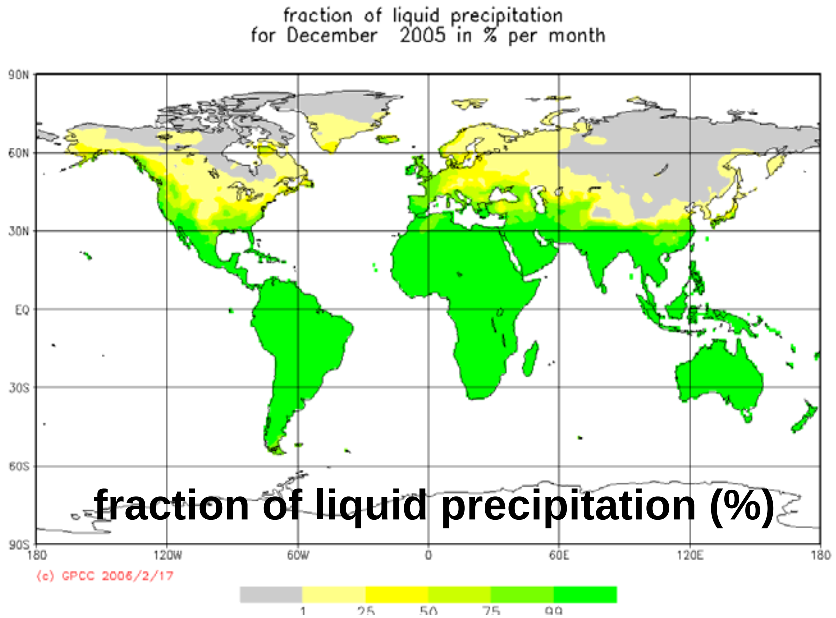


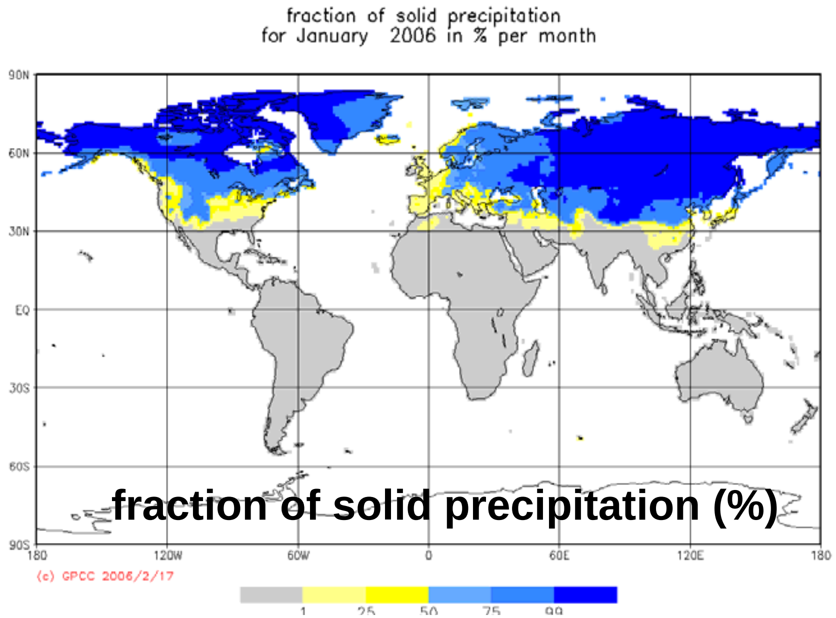


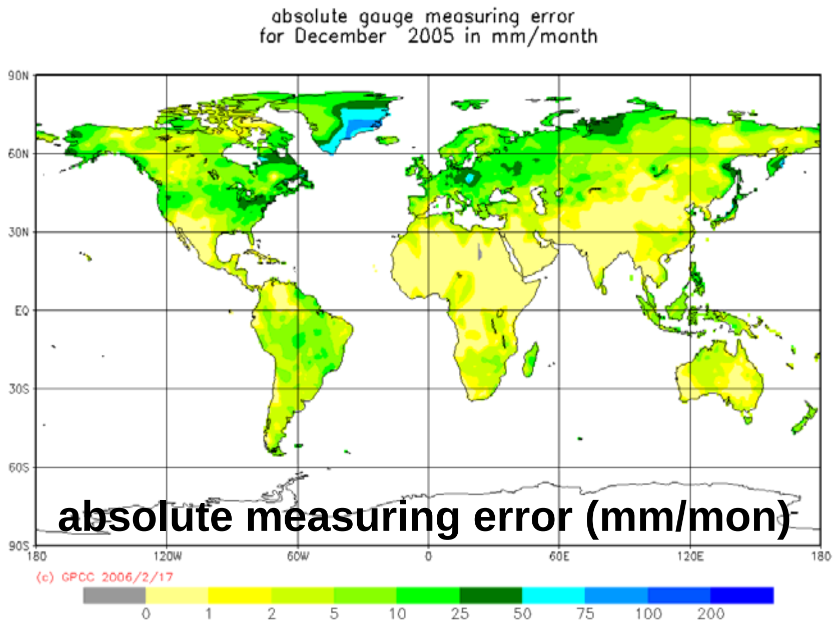
Comparison of monthly percentual corrections in % of observed data derived from daily corrections for the years 1996 and 1997 and long-term mean monthly corrections after Legates 1987

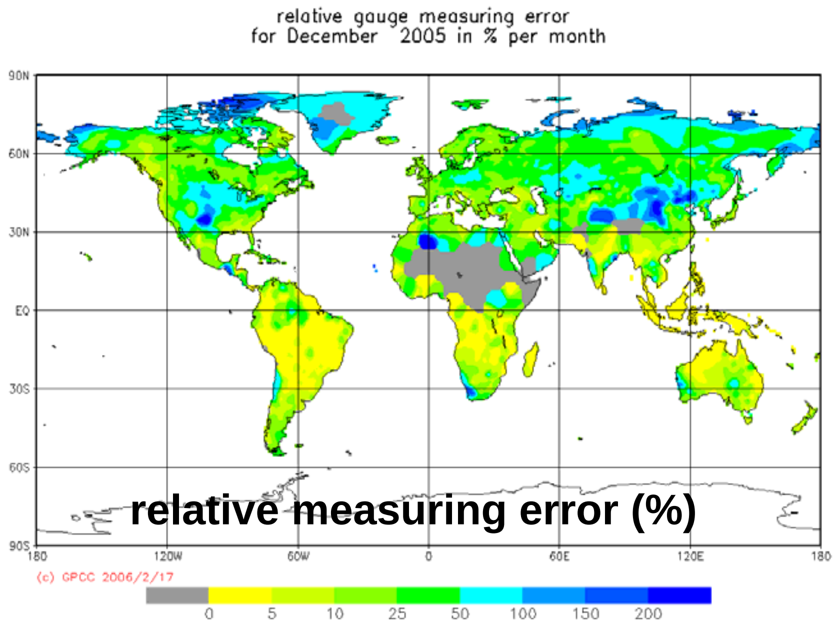
(Ungersböck et al. 2001)

New GPCC products based on synoptic data





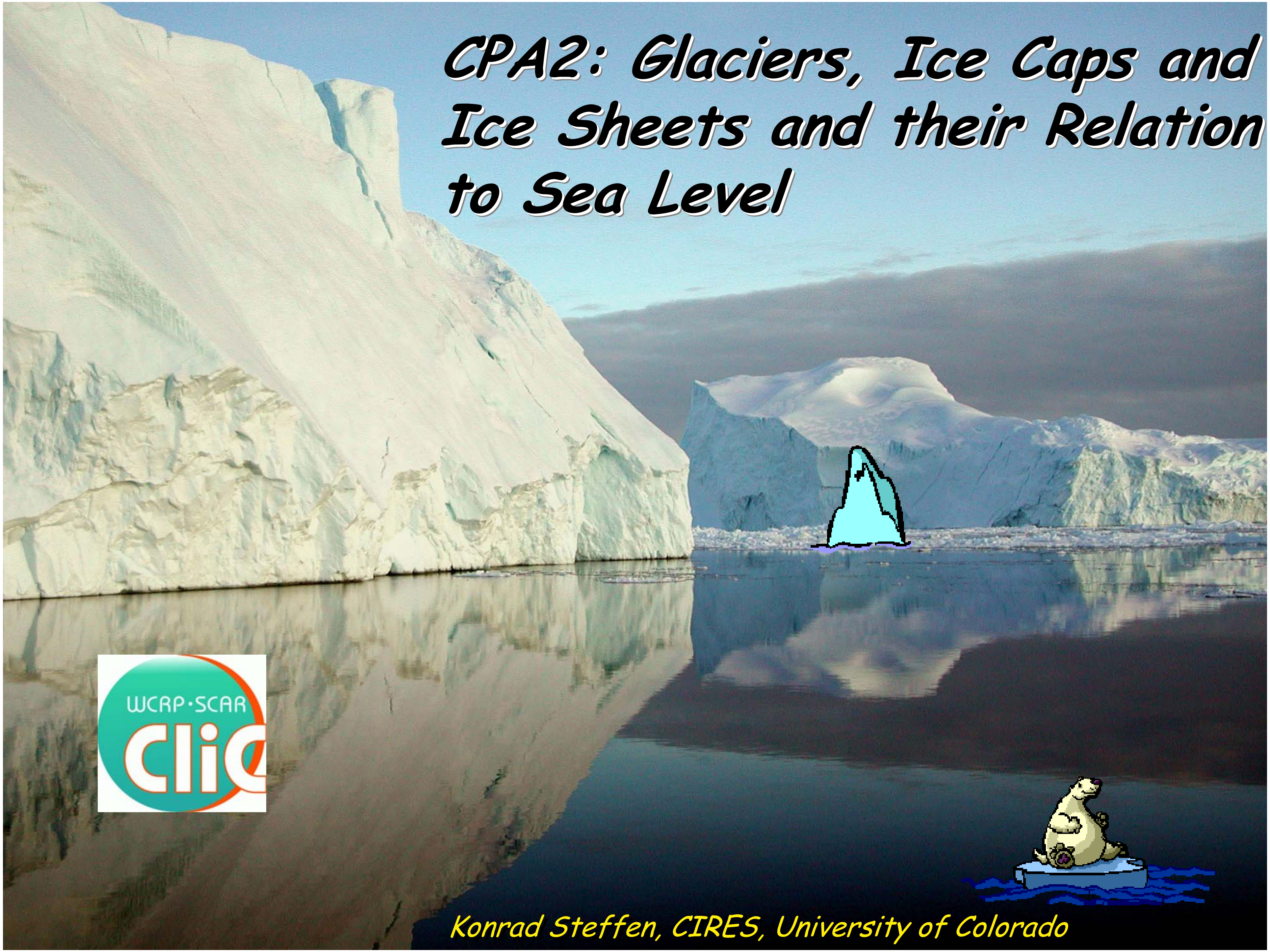




Issues on Extremes

- Data needs: high frequency, sharing
- Analysis of data; tools
- Appropriate output from models (high frequency stats)
- Analysis of model output and comparisons with obs
- Ability and utility of models
- Improvements of models (intensity, frequency etc)
- Improvements in resolution
- Impacts
- Forecasts, predictions, risk
- Translating information into useful decisions
- Stakeholder and user needs

CPA2: Glaciers, Ice Caps and Ice Sheets and their Relation to Sea Level



Konrad Steffen, CIRES, University of Colorado

CliC CPA2. Glaciers, Ice Caps and Ice Sheets and their Relation to Sea Level

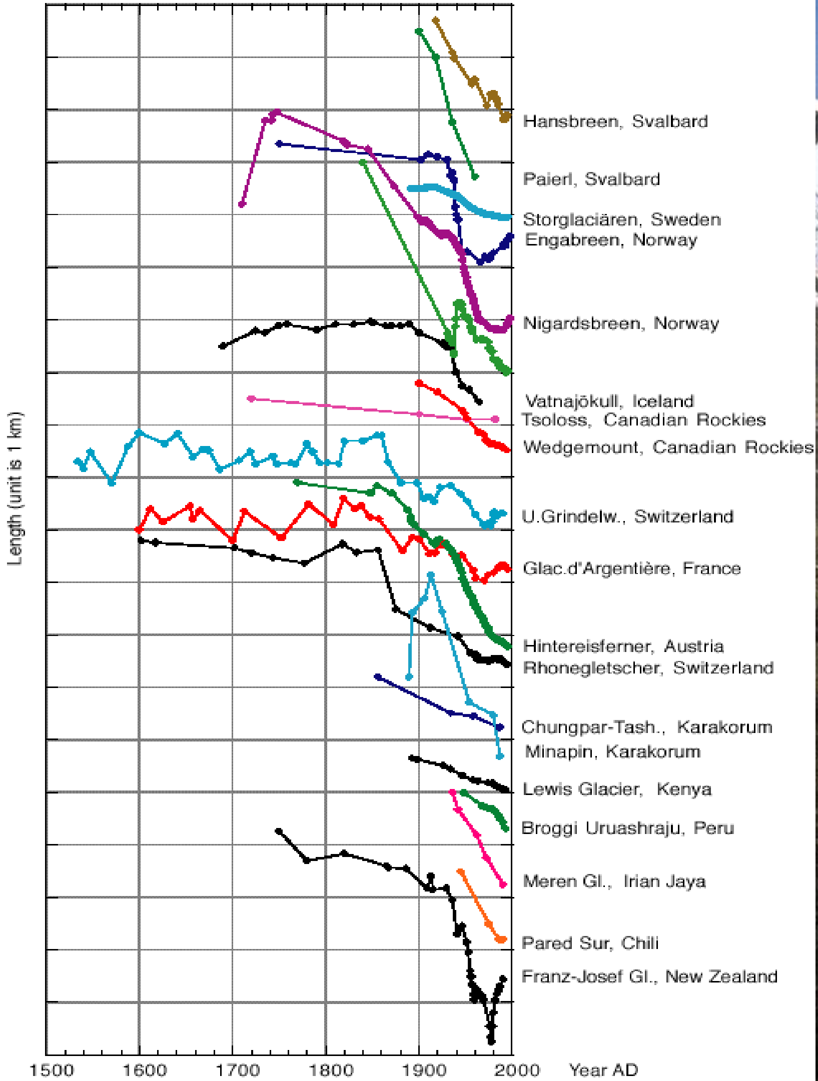
Major objectives:

- ***to improve direct estimates of the mass balances of the Antarctic and Greenland ice sheets and their contribution to sea level changes;***
- ***to develop enhanced capability to estimate past and predict future ice sheet change;***
- ***to implement a system for monitoring, assessing and predicting glaciers and ice caps globally to determine their contribution to mean sea level changes.***

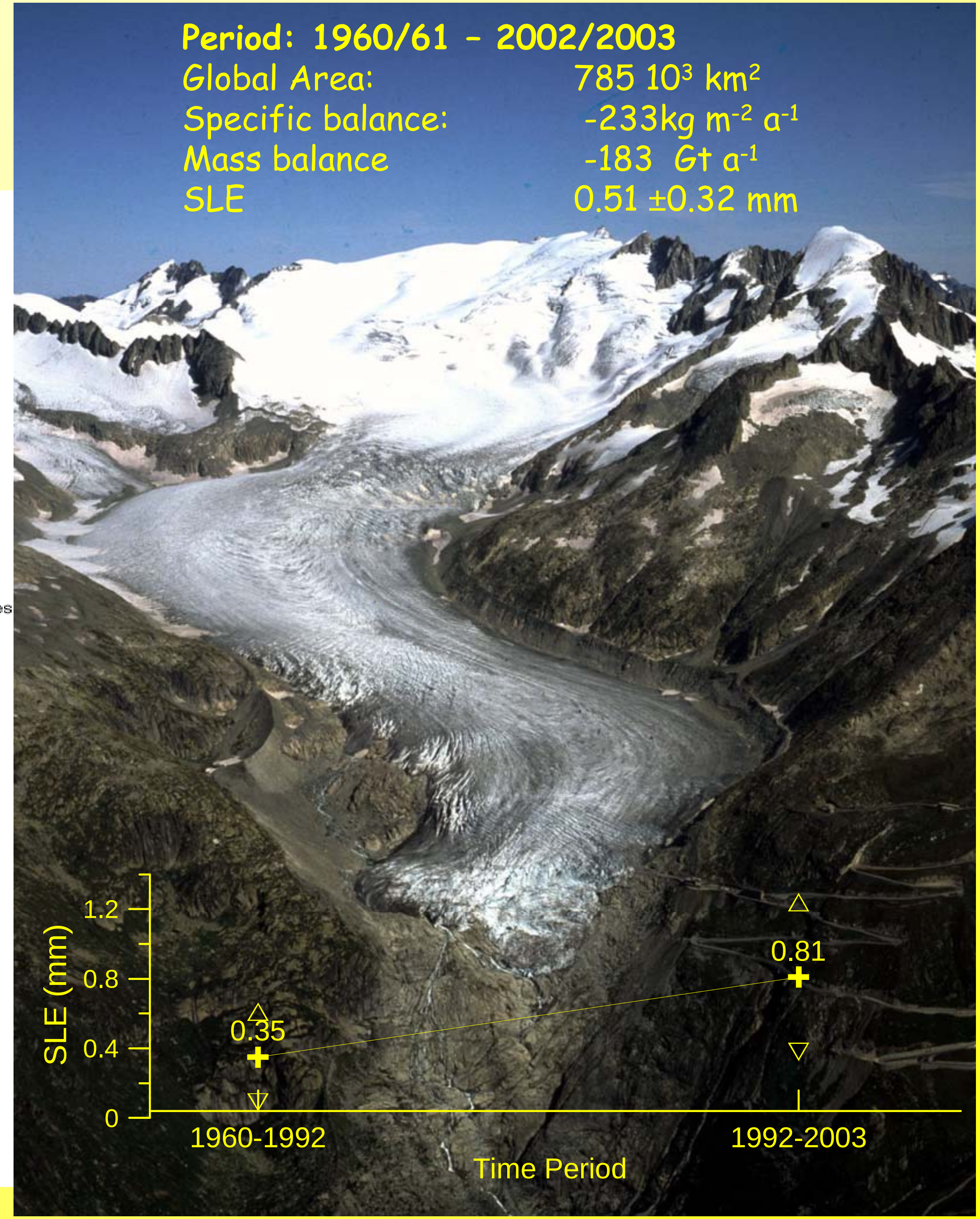
Key Questions:

- ***What are range and uncertainties of the mass balance of the major ice sheets?***
- ***What is the contribution of glaciers, ice caps and ice sheets to changes in global sea level on decadal-to-century time scales?***

Glaciers



Hansbreen, Svalbard
Paierl, Svalbard
Storglaciären, Sweden
Engabreen, Norway
Nigardsbreen, Norway
Vatnajökull, Iceland
Tsoloss, Canadian Rockies
Wedgemount, Canadian Rockies
U.Grindelw., Switzerland
Glac.d'Argentière, France
Hintereisferner, Austria
Rhonegletscher, Switzerland
Chungpar-Tash., Karakorum
Minapin, Karakorum
Lewis Glacier, Kenya
Broggi Uruashraju, Peru
Meren Gl., Irian Jaya
Pared Sur, Chili
Franz-Josef Gl., New Zealand
Length (unit is 1 km)
1500 1600 1700 1800 1900 2000
Year AD

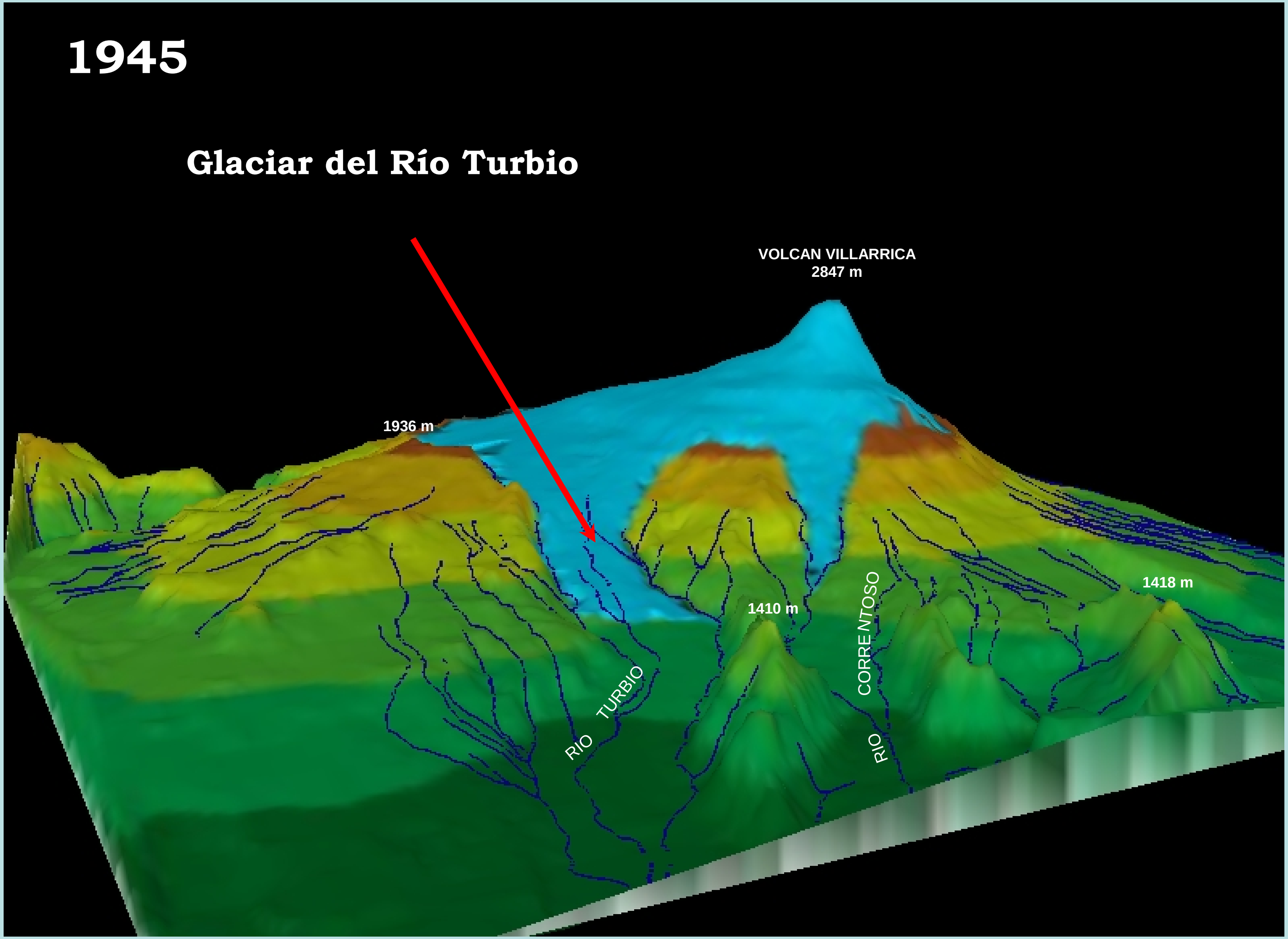


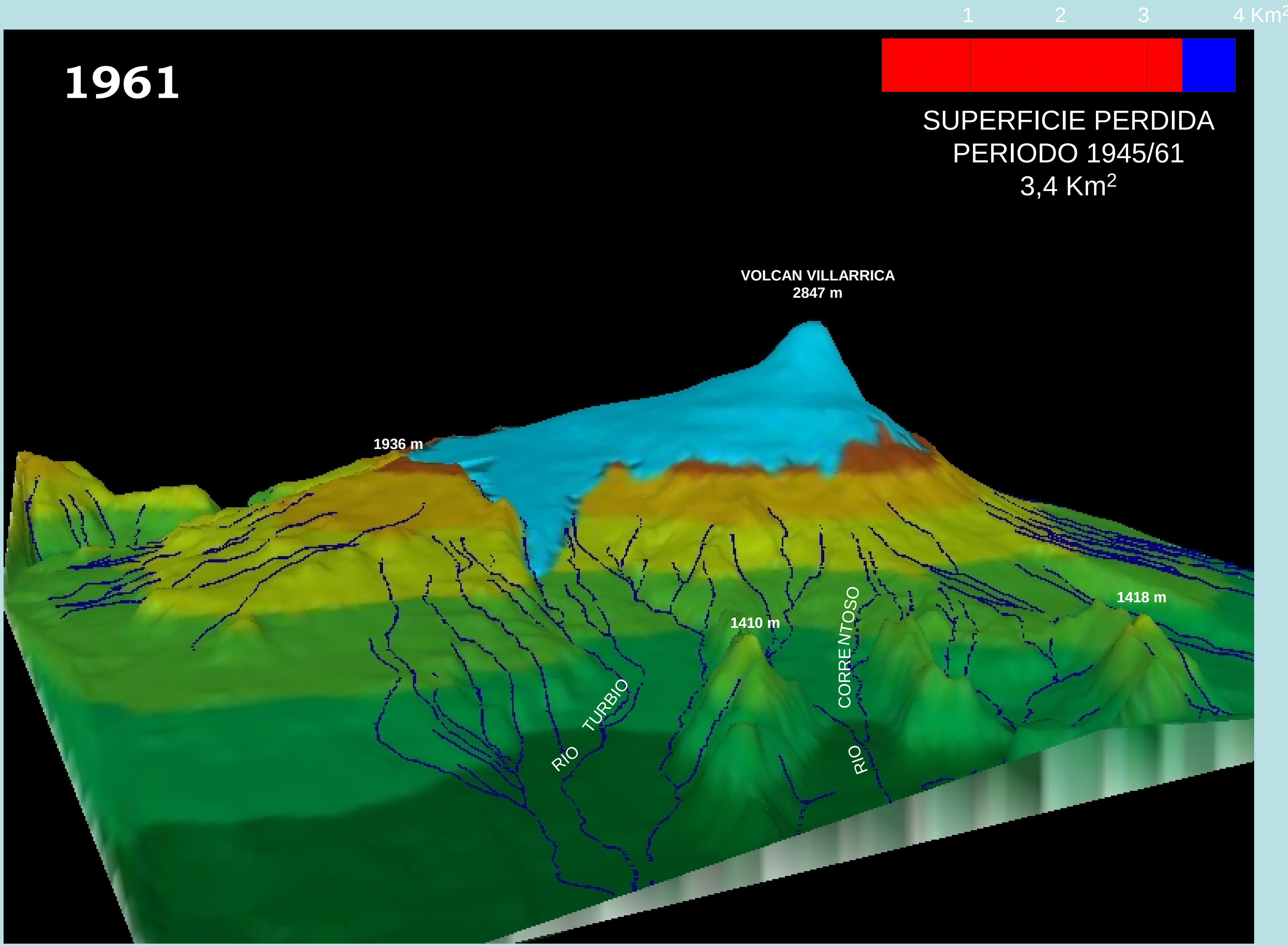
Period: 1960/61 – 2002/2003
Global Area: 785 10³ km²
Specific balance: -233kg m⁻² a⁻¹
Mass balance -183 Gt a⁻¹
SLE 0.51 ±0.32 mm
SLE (mm)
0 0.4 0.8 1.2
0.35
0.81
1960-1992
1992-2003
Time Period

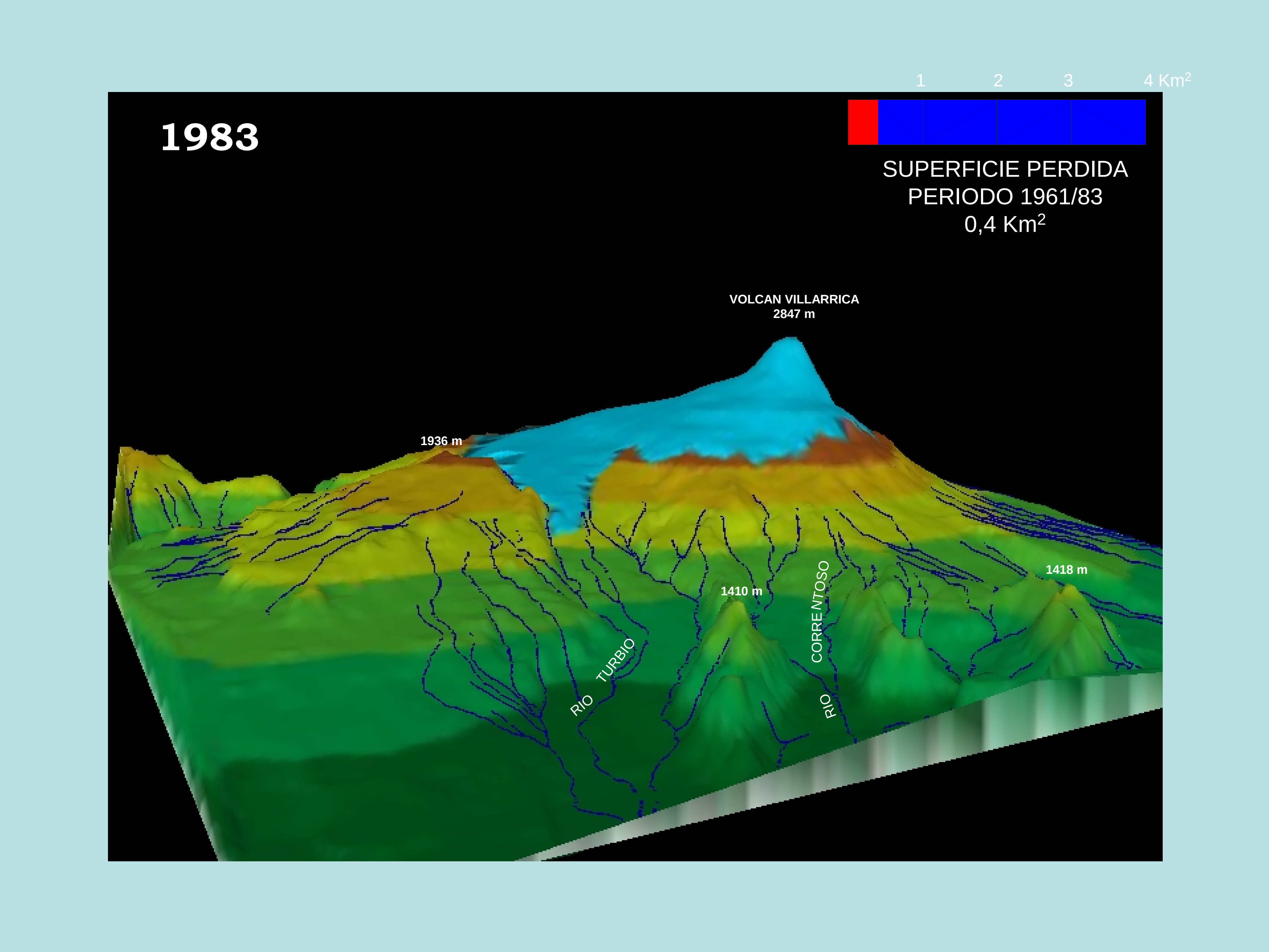
Sea Level Contributions

Region	1960 Volume (km^3)	2000 Volume (km^3)	Volume Change (km^3)	Elevation change (m w.e.)	Sea level (mm)
N.Ellesmere	7095	6883	-212	-6.9	0.53
Agassiz	6158	6091	-67	-2.8	0.17
Axel/Meighen	2564	2535	-29	-2.1	0.07
POW	5897	5842	-55	-2.5	0.14
S.Ellesmere	1941	1849	-92	-7.7	0.23
Devon	4112	3976	-136	-8	0.34
QEI	**27767**	**27176**	**-591**	**-5**	**1.47**

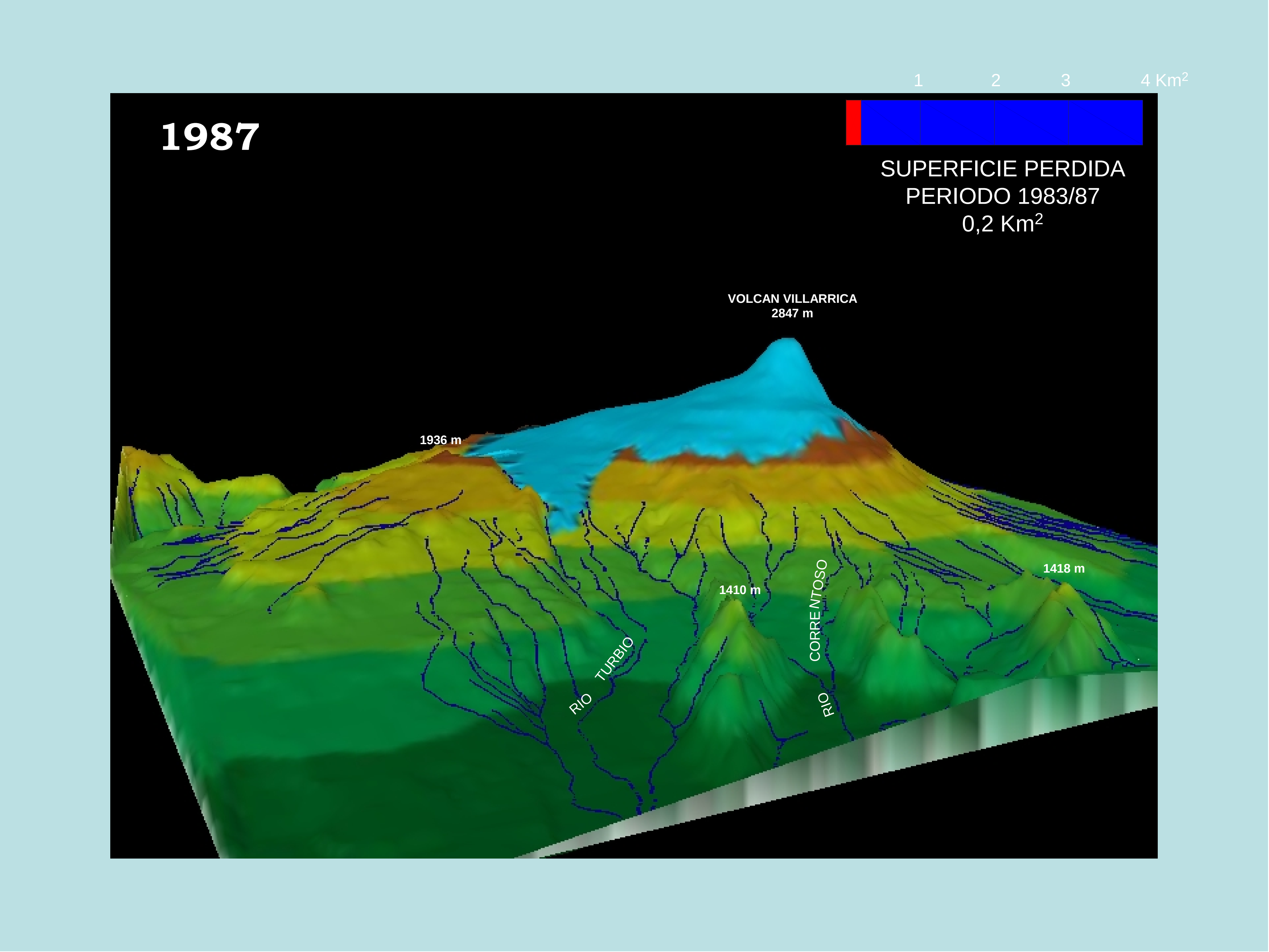
(Sharp, U. Alberta, in review)

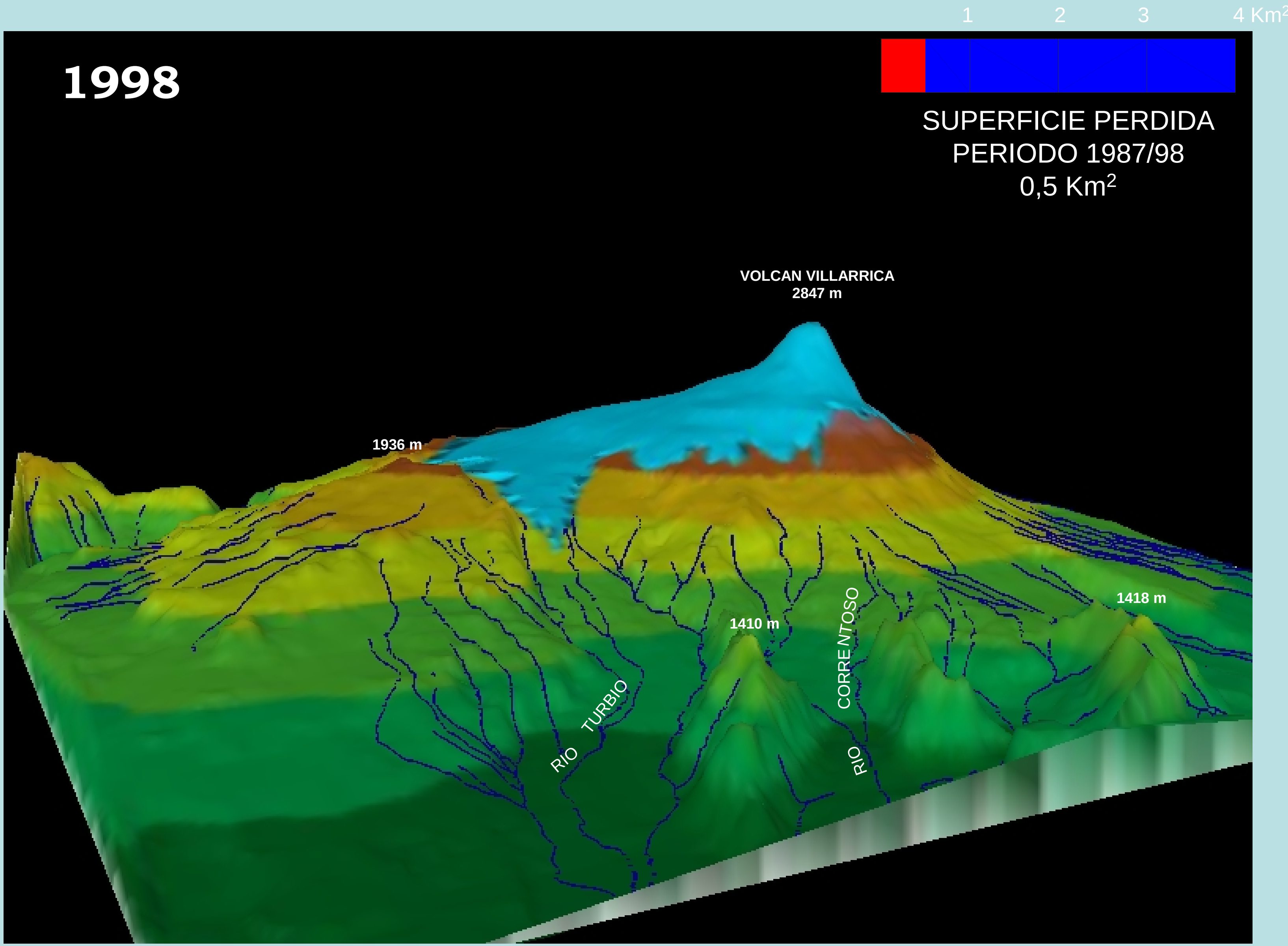

1945
Glaciar del Río Turbio
VOLCAN VILLARRICA
2847 m
1936 m
1410 m
1418 m
RIO TURBIO
RIO CORRENTOSO

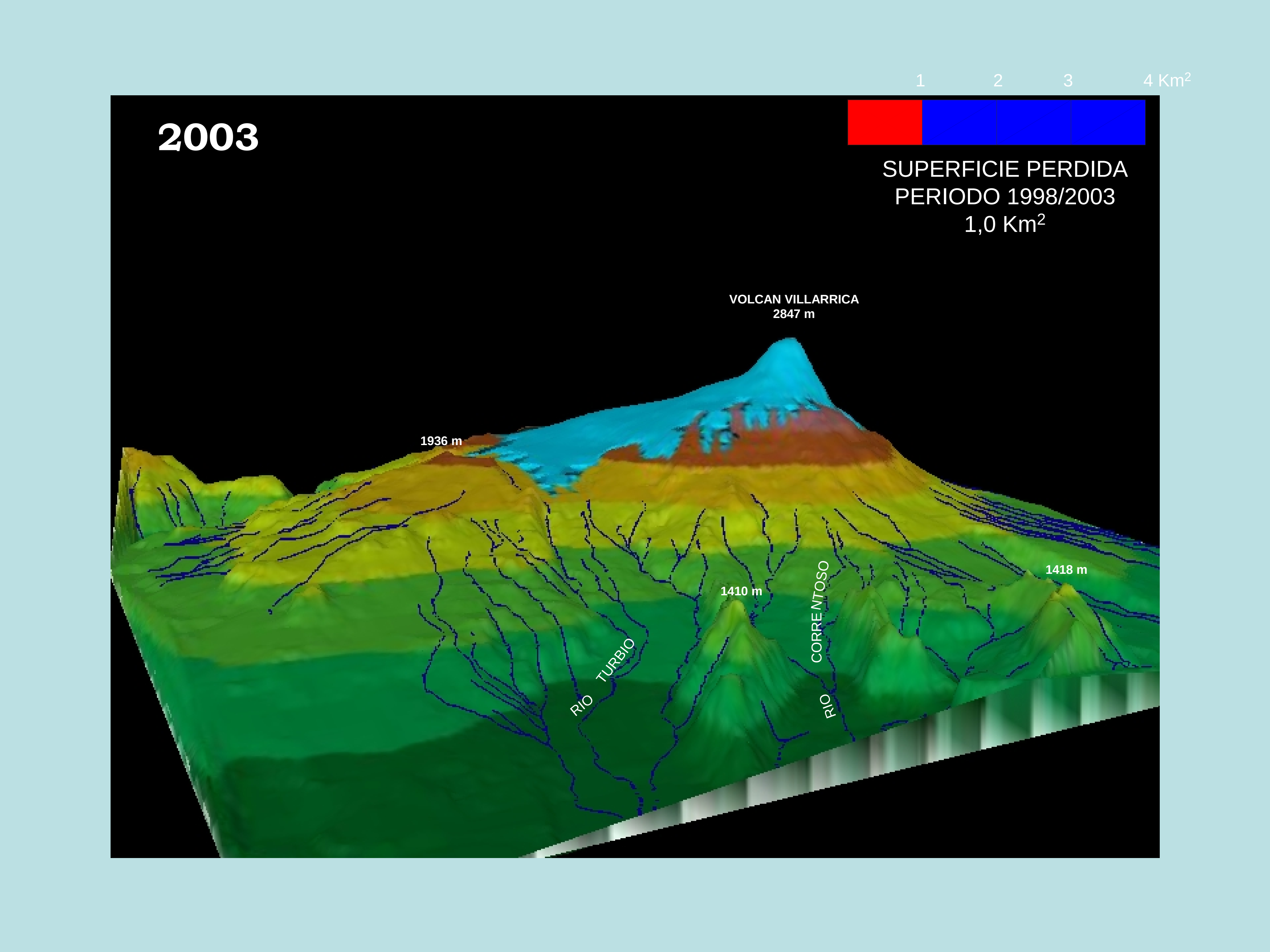

1961
1 2 3 4 Km2
SUPERFICIE PERDIDA
PERIODO 1945/61
3,4 Km2
VOLCAN VILLARRICA
2847 m
1936 m
1410 m
1418 m
RIO TURBIO
RIO CORRENTOSO



1983
1
2
3
4 Km2
SUPERFICIE PERDIDA
PERIODO 1961/83
0,4 Km2
VOLCAN VILLARRICA
2847 m
1936 m
1410 m
1418 m
RIO TURBIO
RIO CORRENTOSO


1987
1
2
3
4 Km2
SUPERFICIE PERDIDA
PERIODO 1983/87
0,2 Km2
VOLCAN VILLARRICA
2847 m
1936 m
1418 m
1410 m
RIO TURBIO
RIO CORRENTOSO


1998
1 2 3 4 Km2
SUPERFICIE PERDIDA
PERIODO 1987/98
0,5 Km2
VOLCAN VILLARRICA
2847 m
1936 m
1410 m
1418 m
RIO TURBIO
RIO CORRENTOSO



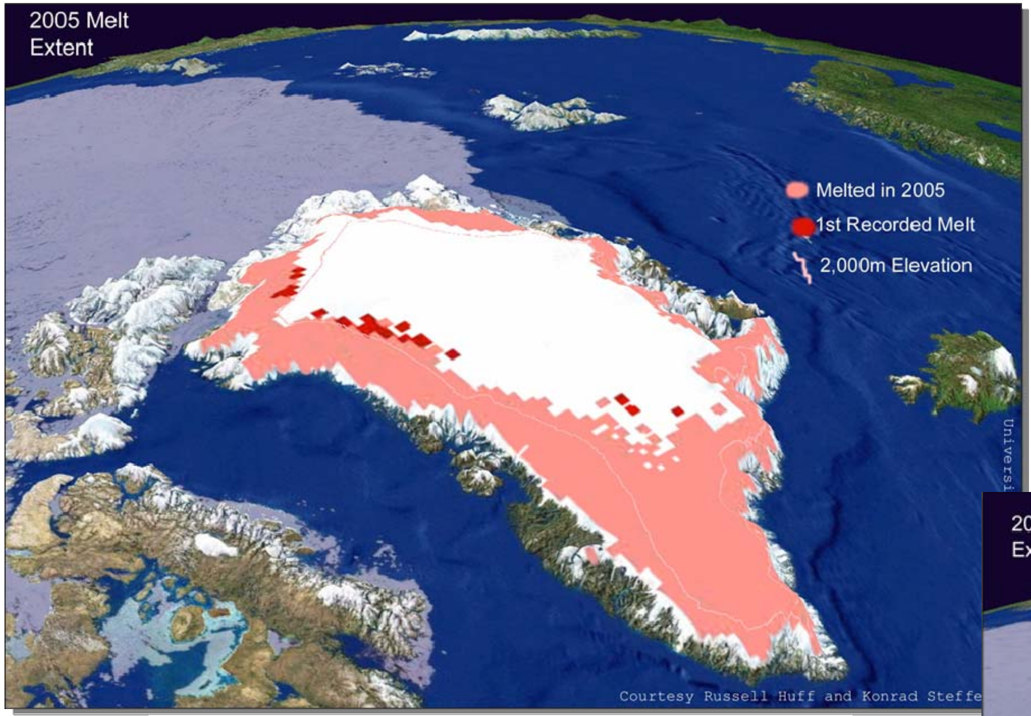
2003
1
2
3
4 Km2
SUPERFICIE PERDIDA
PERIODO 1998/2003
1,0 Km2
VOLCAN VILLARRICA
2847 m
1936 m
1418 m
1410 m
RIO TURBIO
RIO CORRENTOSO

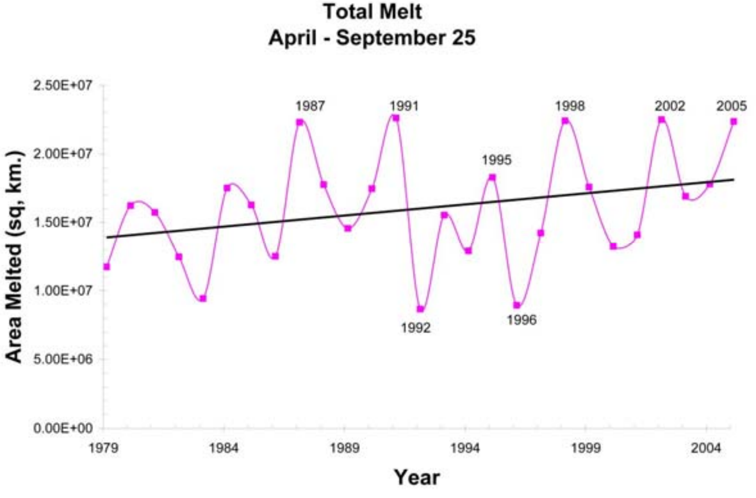
Current Ice Sheet/Glacier Contributions to Sea Level Rise

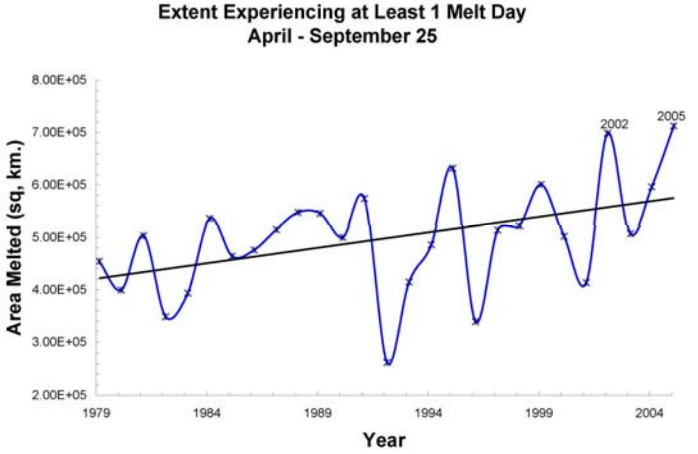
Ice-Covered Region	Sea Level Input (mm/yr)	
Canadian Ice Caps[1]		+0.065 (1995-2000)
Patagonian Ice Fields[2]	+0.042 (1968/75 - 2000)	+0.105 (1995-2000)
Alaskan Glaciers[3]	+0.14 (mid 50s - mid 90s)	+0.27 (1995-2000)
Greenland[4]	+0.13 (1993/4 -1998/9)	+0.20 (1997-2003)
Pine Island[5,6]	+0.01 (1992-1999)	+0.24 (2002-2003)
Antarctica[7]		0.00 (1993–2003)

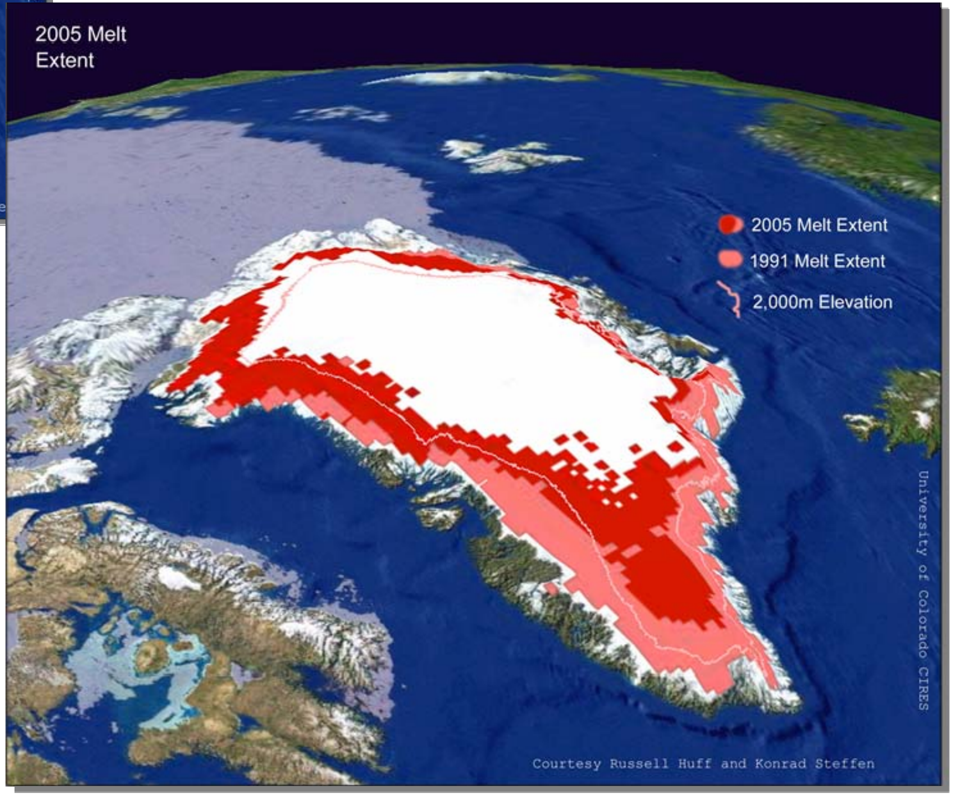
References.1: Abdalati et al., *JGR*, 2004; 2: Rignot et al., *Science*, **302**, 2003; 3: Ahrendt et al., *Science*, 2002; 4:Krabill et al., *Science*, **289**, 2000 & *GRL*, 2005; 5: Shepherd et al., *GRL*, **29**, 2002; 6: Thomas et al., *Science*, **306**, 2004; 7: Rignot et al., *GRL*, **31**,2004.

Greenland Ice sheet Melt Extent 2005 – another record melt year



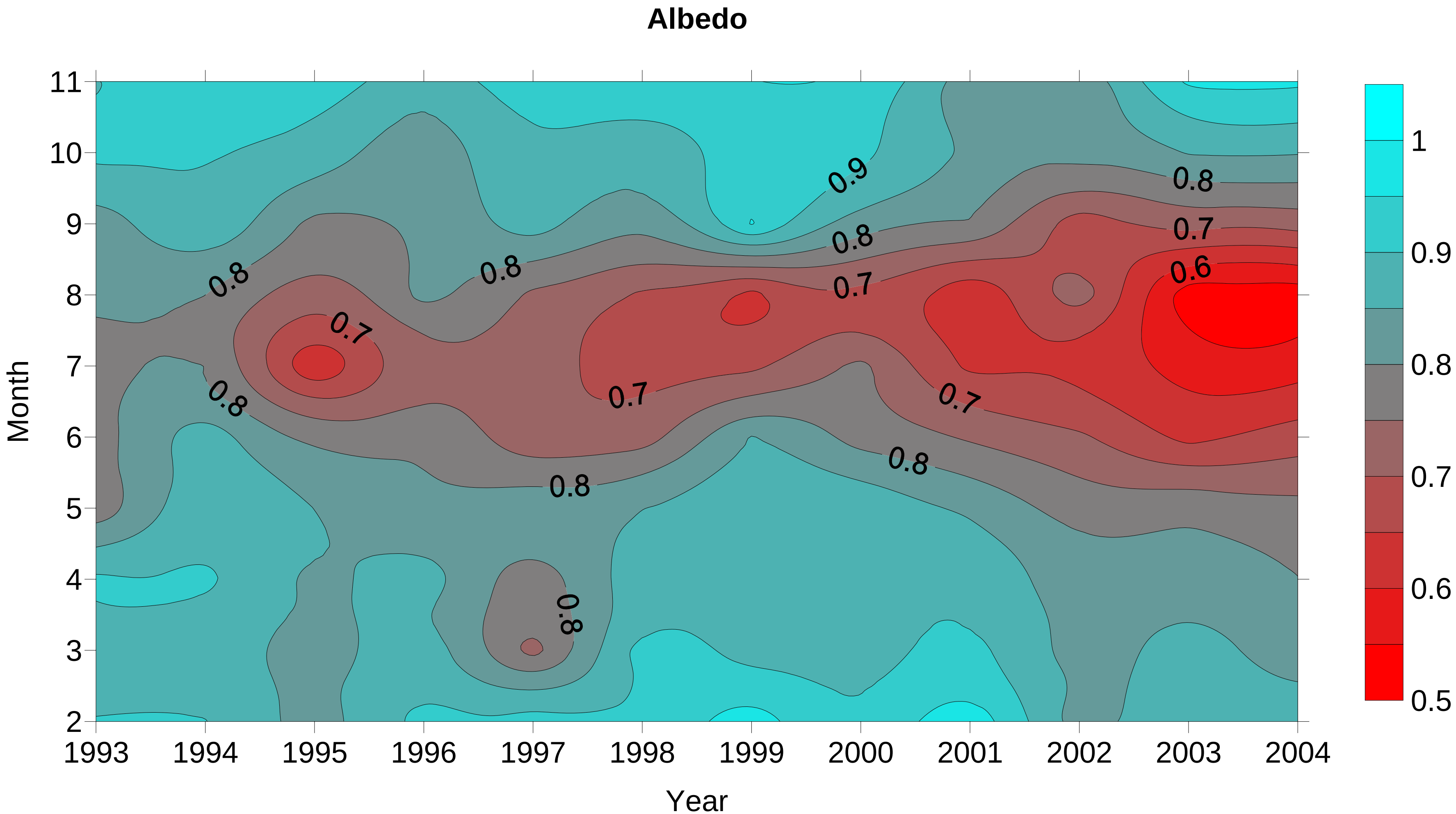






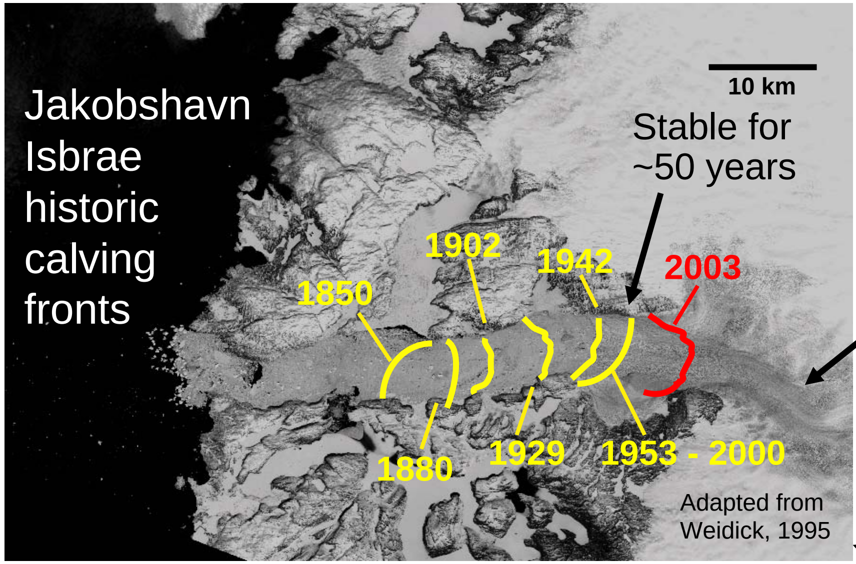
Konrad Steffen and Russell Huff, CIRES, University of Colorado
http://cires.colorado.edu/science/groups/steffen/greenland/melt2005/

Interannual Albedo Variability
Swiss Camp AWS: 1993 through 2004

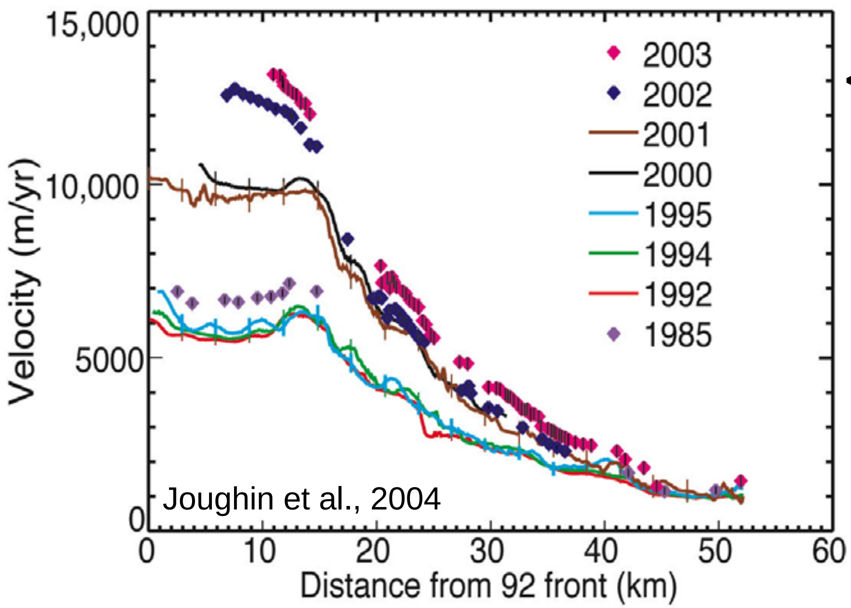


Surface mass balance is negative (~2.5 m) since 1990

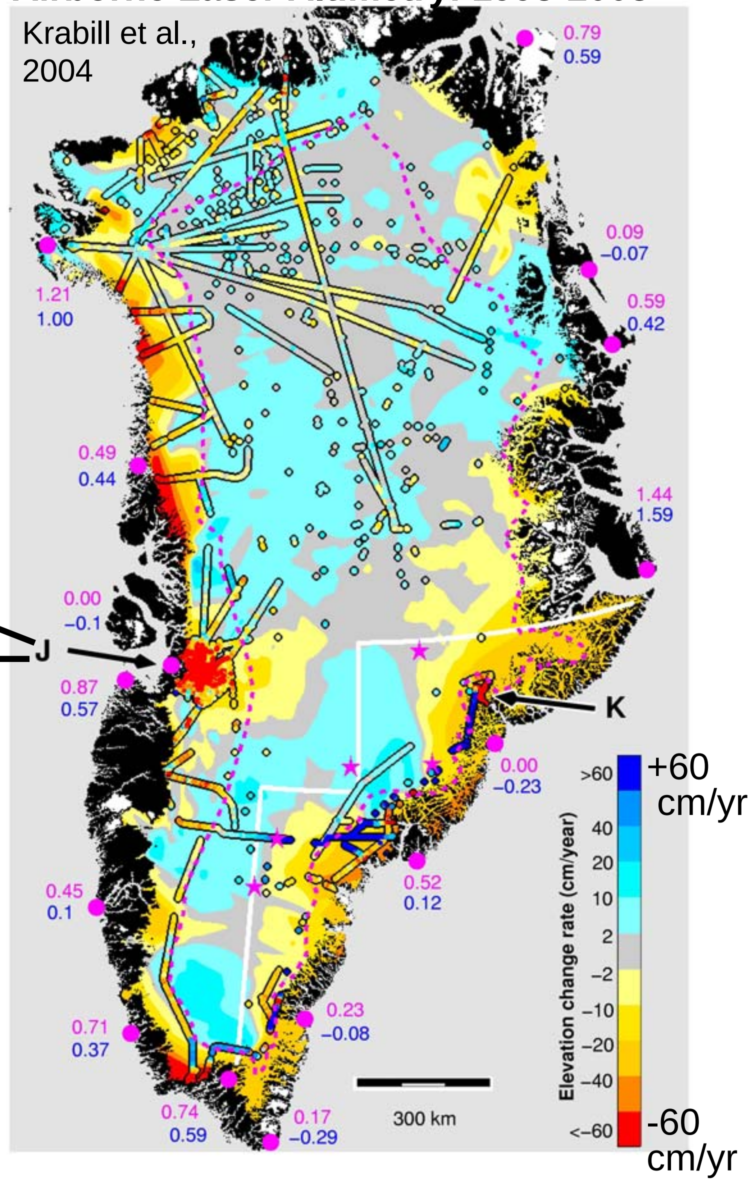
Greenland Margins: Where the Action Is



90 m thinning between 1997-2003



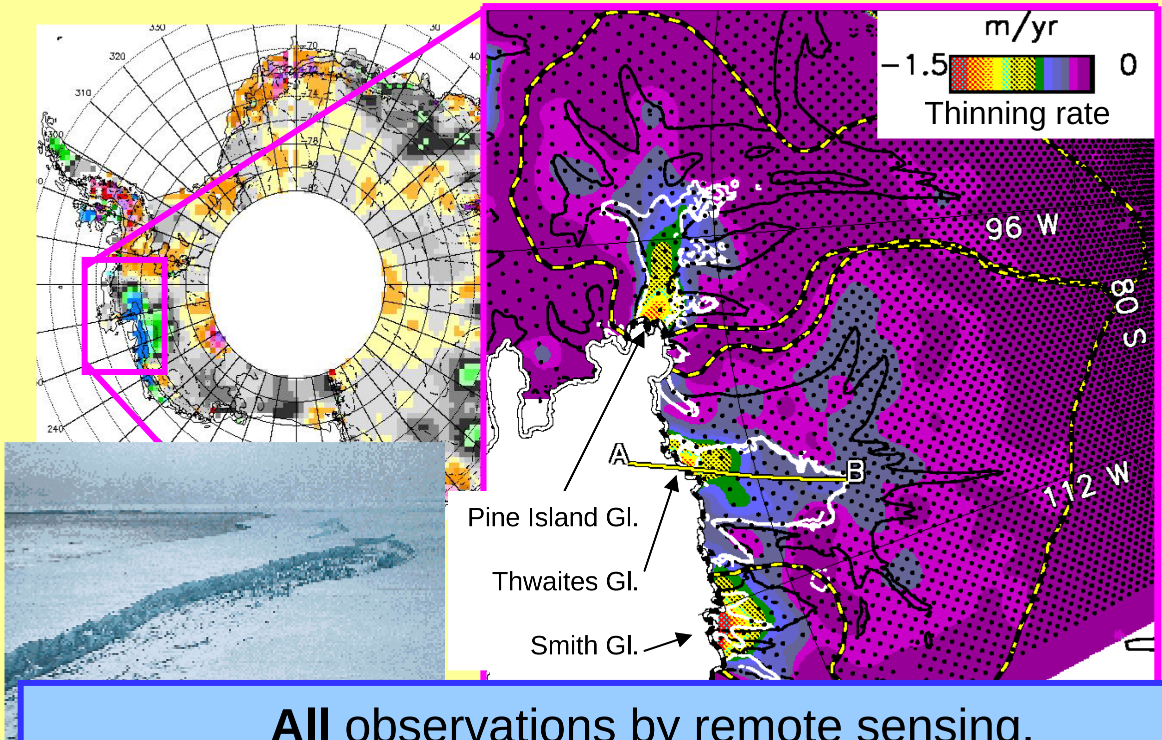
Airborne Laser Altimetry: 1993-2003



1997-2003 neg. balance up 33% over mid/late 1990s rate to 80 km^3/yr (.20 mm/yr sea level rise)

Regional Collapse in Antarctica

Major portion of West Antarctic ice sheet exhibits expected signs of collapsing



- Thinning increasing towards coast (satellite and aircraft altimetry)
- Flow acceleration (InSAR)
- Retreat of grounding line (Landsat and InSAR)
- Calving of large icebergs (MODIS)

All observations by remote sensing.
Most of this area has **never** been visited by humans.

The "action" is near the steep rough coasts
where satellite radar altimetry are severely limited

Greenland change in height and mass change, Zwally et al 2005

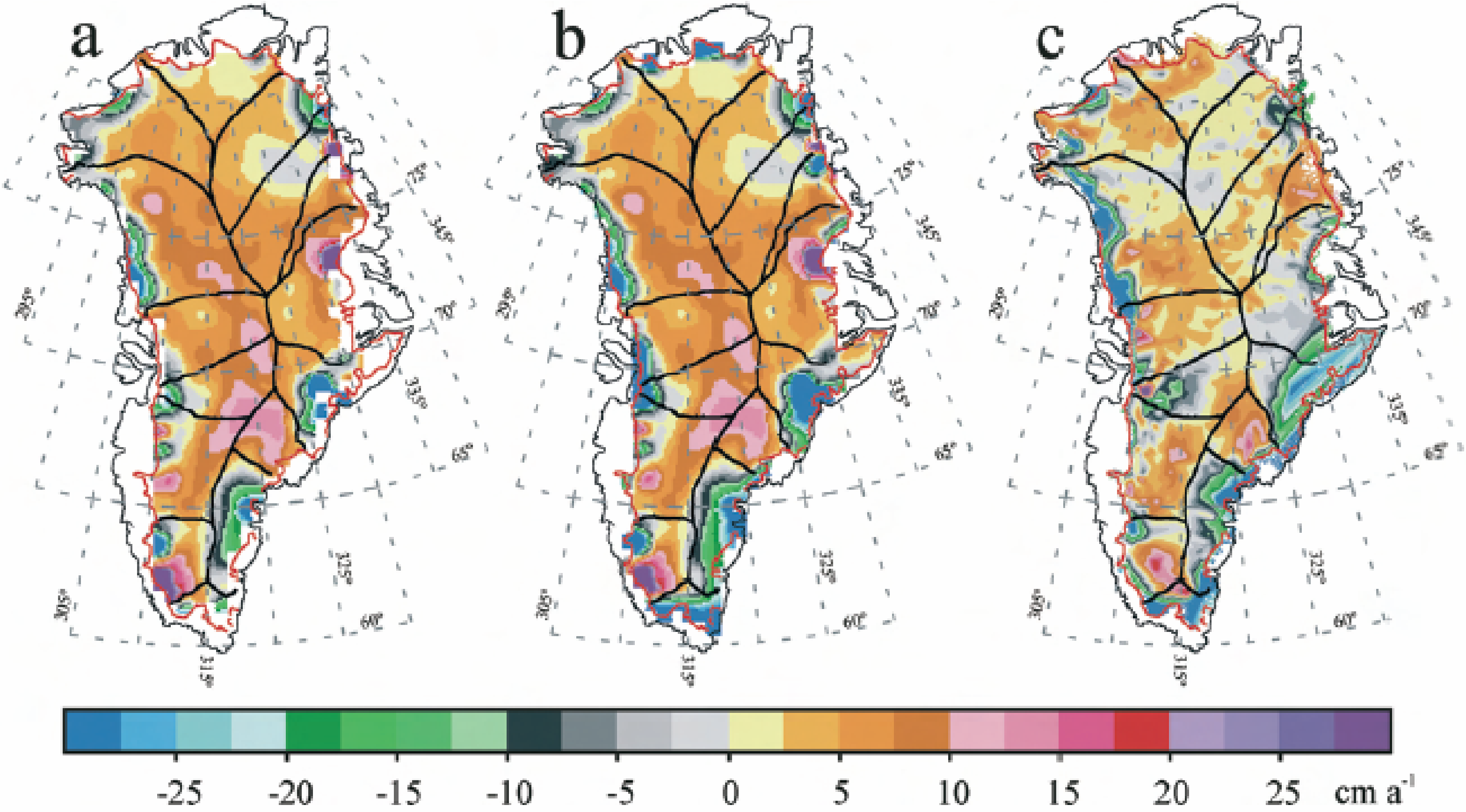
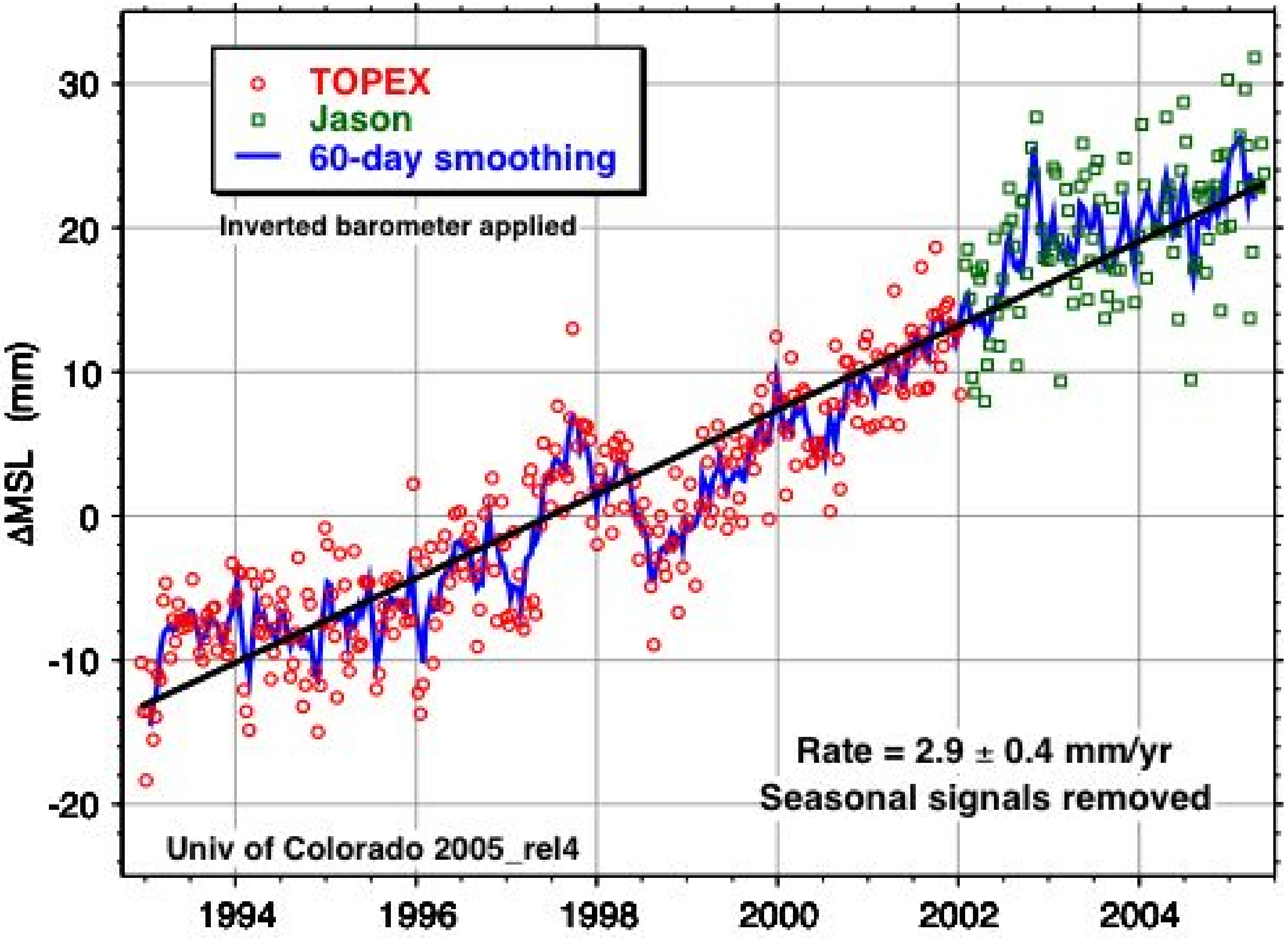


Fig. 5. Comparison of *dH/dt* distribution for Greenland: (a) ERS only; (b) same as in Figure 1b; and (c) produced by interpolation and extrapolation of airborne laser altimeter and ATM surveys data collected in 1993–99 (Krabill and others, 2000).

thinning at the margins (-42 ± 2 Gt a^{-1} below the equilibrium-line altitude (ELA)) and growing inland ($+53 \pm 2$ Gt a^{-1} above the ELA) with a small overall mass gain ($+11 \pm 3$ Gt a^{-1}; -0.03 mm a^{-1} SLE (sea-level equivalent)). The ice sheet in West Antarctica (WA) is losing mass (-47 ± 4 Gt a^{-1}) and the ice sheet in East Antarctica (EA) shows a small mass gain ($+16 \pm 11$ Gt a^{-1}) for a combined net change of -31 ± 12 Gt a^{-1} ($+0.08$ mm a^{-1} SLE). The contribution of the three ice sheets to sea level is $+0.05 \pm 0.03$ mm a^{-1}. The

Sea level is rising:
from ocean expansion and melting glaciers



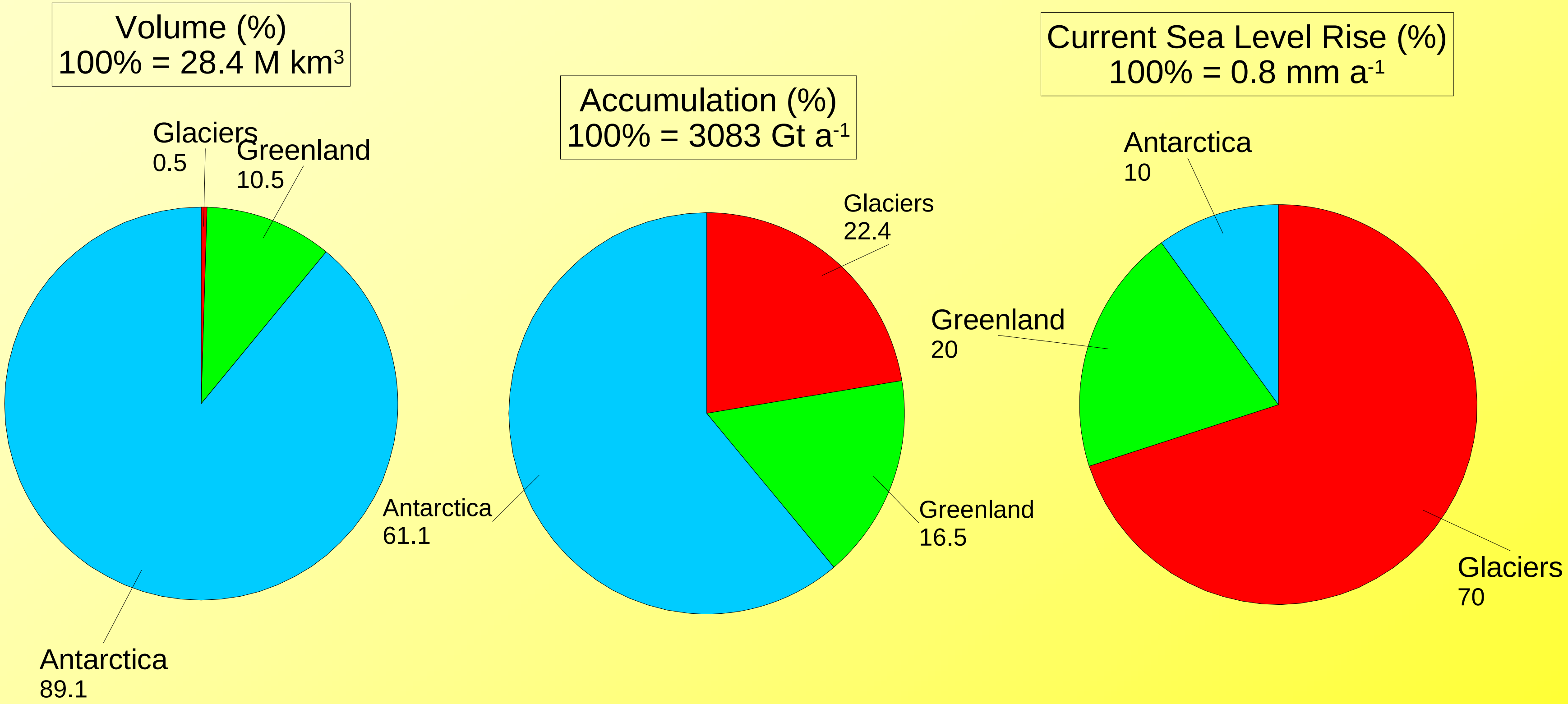
Since 1993 Global sea level has risen 37 mm (1.46 inches)

- 60% from expansion as ocean temperatures rise,
- 40% from melting glaciers

Steve Nerem

Extremes: High tides, storm surges, tsunamis

Summary: Cryospheric SLR



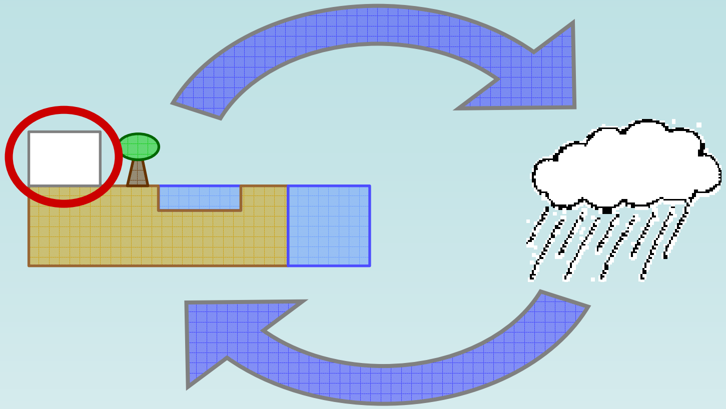
Comparison of total volume (left), total annual accumulation (middle), and total contribution to sea-level rise (right) for small glacier/ice caps and the ice sheets in Greenland and Antarctica

Some Challenges for Sea Level Rise and Variability

- Prediction of the broader climate/Earth system
- Prediction problem
  - medium and long range: decades, centuries
- Coordinate & implement activities to exploit fully
  - new & increasing data streams (environmental satellites & in situ observations i.e. the Argo system)
  - growth in capability & availability of computing
  - increasing complexity & breadth of models
  - increasing data assimilation ability
  - → communicate new findings and process understanding
  - → assess uncertainties for model prediction
- Interact efficiently with the climate/Earth system communities involved in sea level change assessment

GLACIERS IN CLIMATE MODELS

- analysis of regional water cycles using **RCMs** and prediction of future changes



⇨ neglection of water stored in **mountain glaciers**

- state-of-the art GCMs and RCMs: **static glacier masks**

⇨
  - exception: coupling of ice sheet models (GCMs)
  - no feedback to climate
  - no runoff generation (water balance not closed)

- not suitable for longterm regional simulations in glacierised areas
- not suitable for hydrological applications

CPA3. The marine cryosphere and its interactions with high latitude oceans and atmosphere

Sea ice response to change and its feedbacks in the climate system?

- *How will sea ice respond in future to a changing climate; for example will the summer Arctic Ocean be ice-free in 50 years?*
- *How will a changing sea-ice cover affect climate through its interactions with the atmosphere and the ocean? (Links to CPA4)*

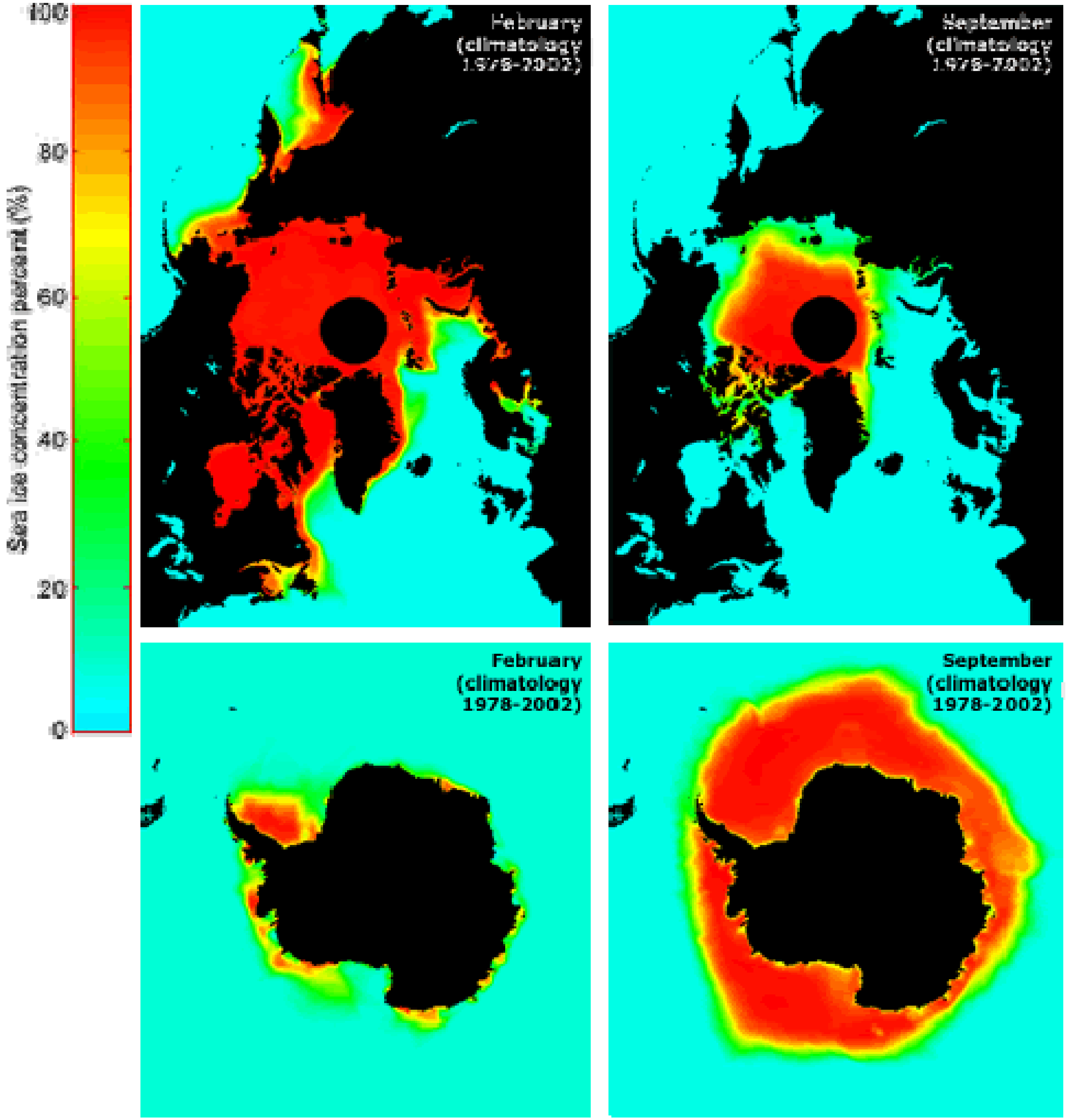
Interaction of the ocean with ice shelves and icebergs

- *How do processes of ice-ocean interaction, including basal melt and marine ice accretion, affect the mass balance and stability of ice shelves?*
- *What is the distribution and variability of freshwater input to the oceans from ice shelves, icebergs and ice-sheet runoff, and what role does this have on ocean circulation (for example maintenance of global thermohaline circulation)?*

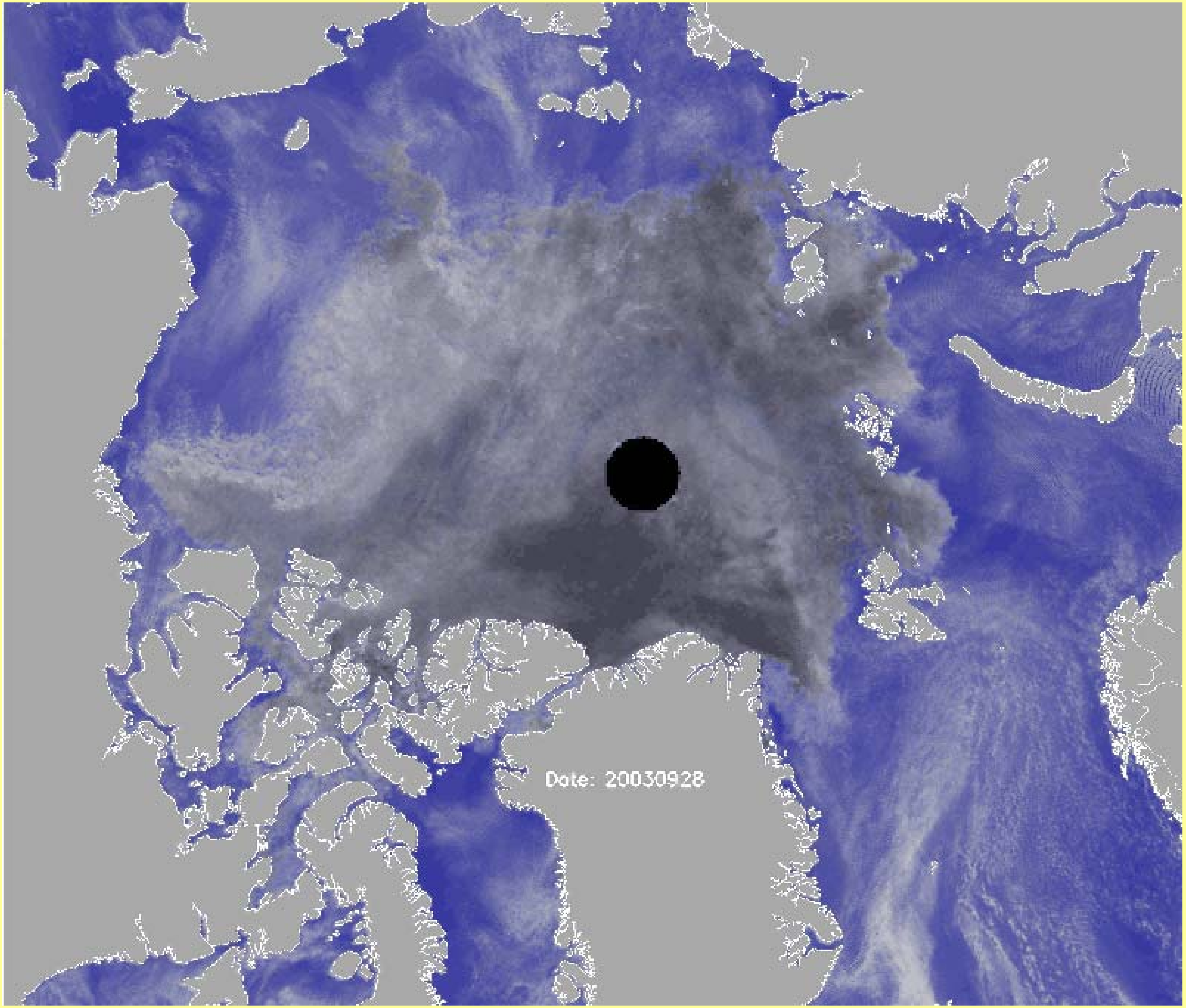
Sea Ice: its present state, its response to change, and its feedbacks in the climate system

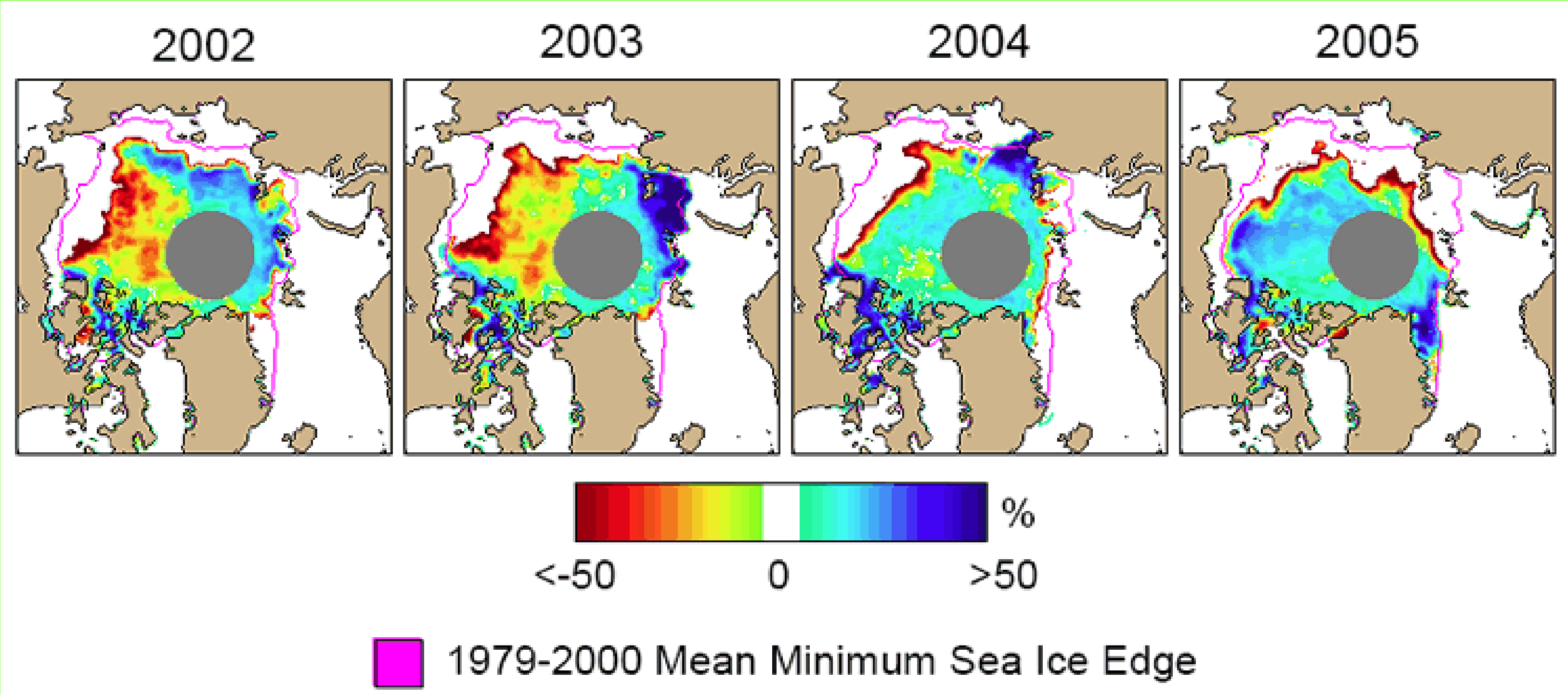
- *What are the present mean state, natural variability and recent trends in sea-ice characteristics in both hemispheres, and what are the physical processes that determine these?*

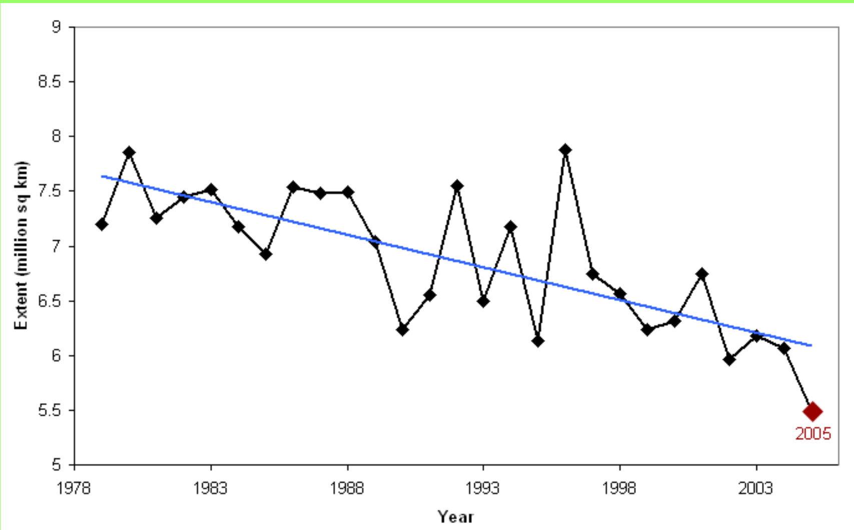
Southern Ocean and Arctic Climate Panels provide advisory role

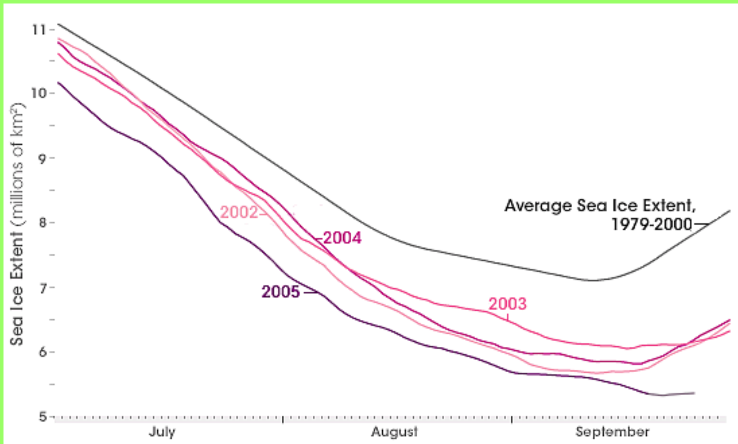

100
80
60
40
20
0
Sea ice concentration percent (%)
February
(climatology
1978-2002)
September
(climatology
1978-2002)
February
(climatology
1978-2002)
September
(climatology
1978-2002)

Sea Ice motion in the Arctic, Winter 2003-2004

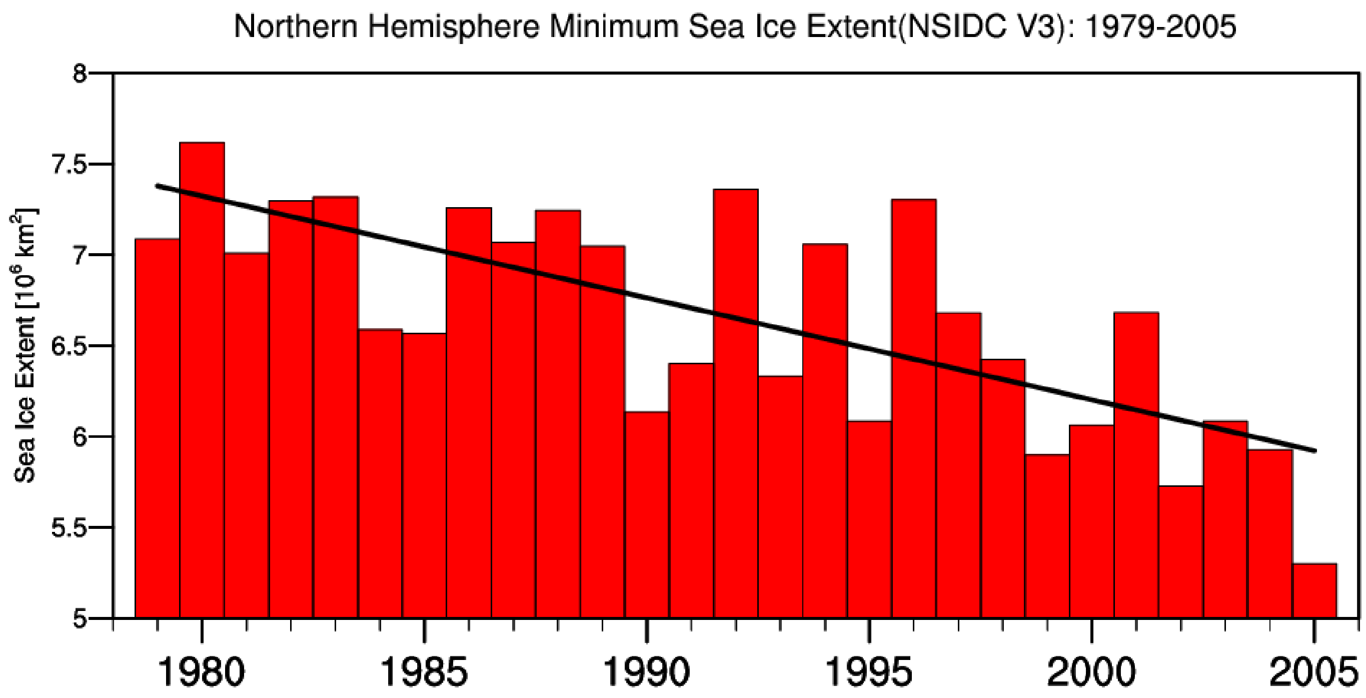


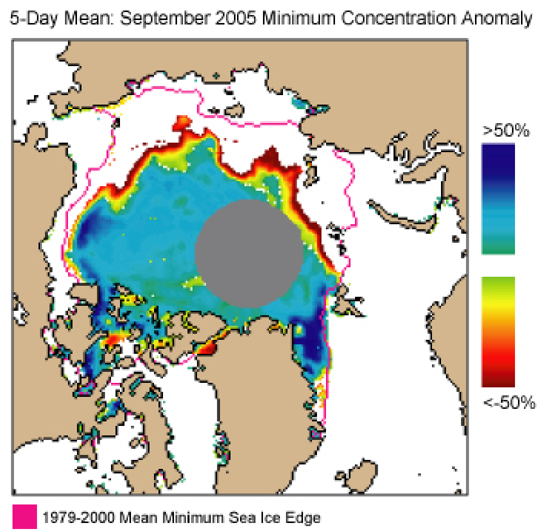


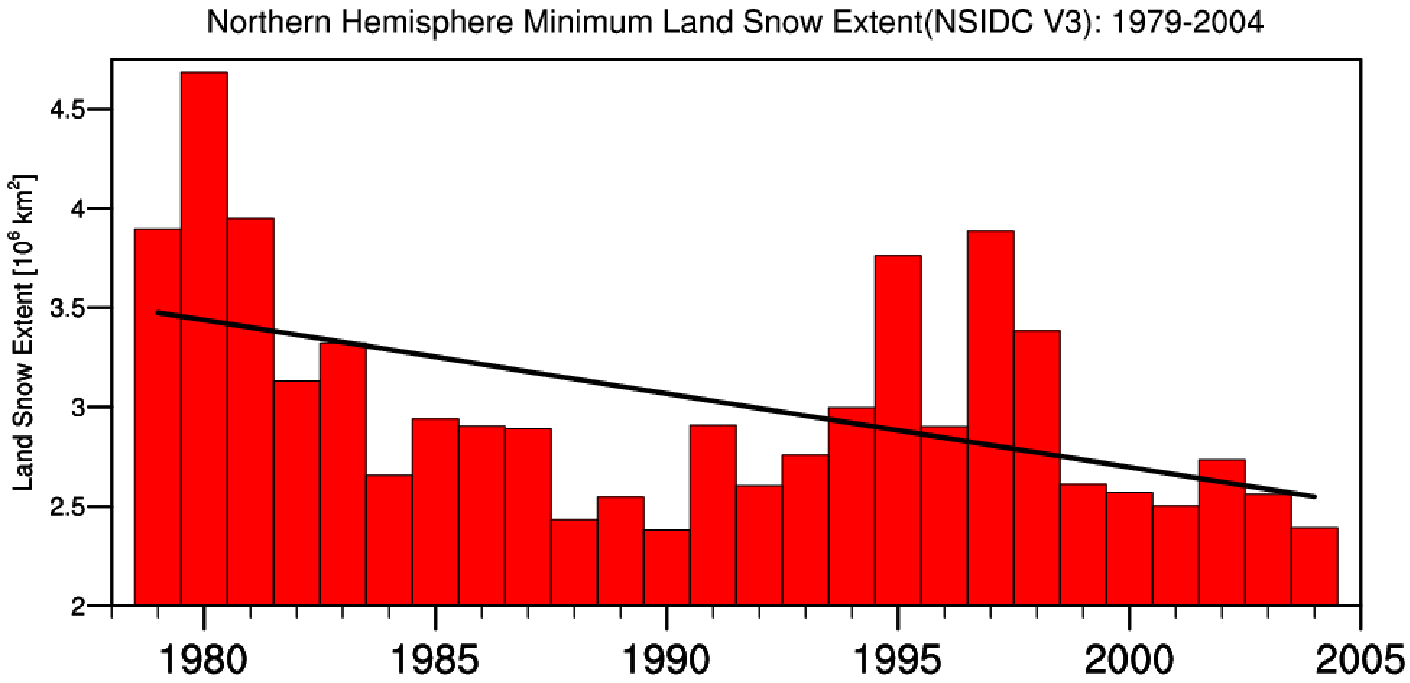




Courtesy NSIDC



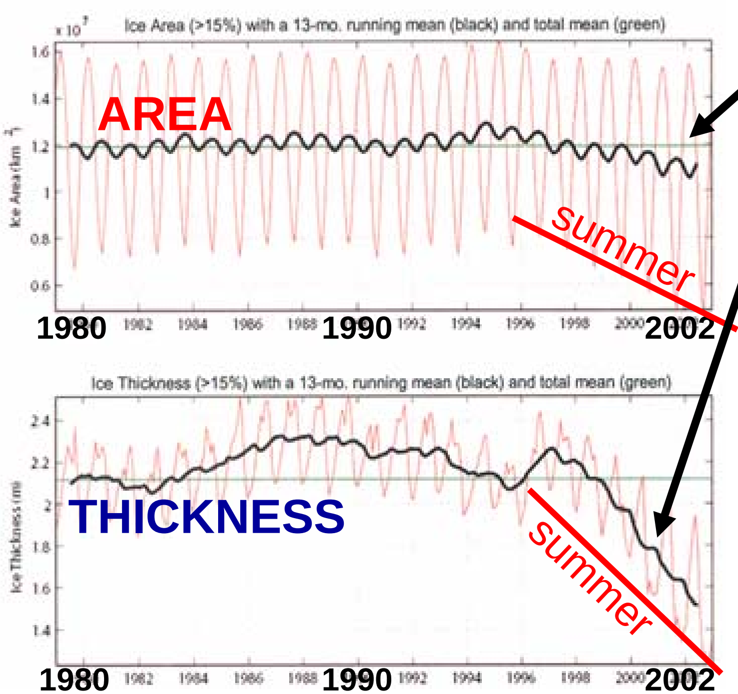




Declines in sea ice and snow cover; and permafrost

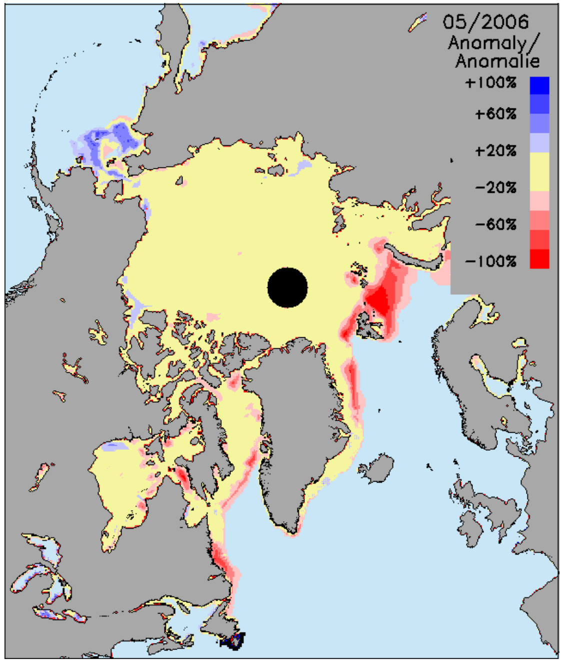
Shrinkage of Arctic Sea Ice Pack

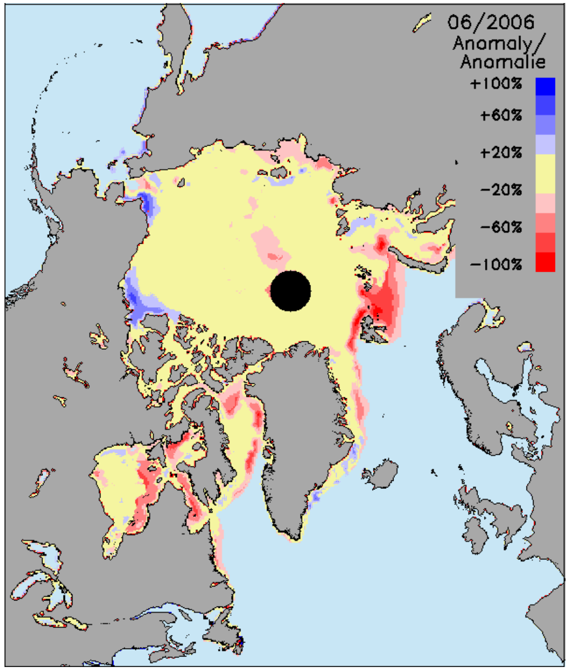
Area of Arctic sea ice in summer has been declining ~10%/decade.



- ❑ Sea Ice-Ocean model driven by known atmospheric forcing suggests that **thickness** of sea ice is reducing even faster than the **area** (W. Maslowski, Naval PS).

- ❑ Observational **verification of thickness change is critical need** to estimate when the Arctic Ocean may be “ice-free” during summer.


05/2006
Anomaly/
Anomalie
+100%
+60%
+20%
-20%
-60%
-100%


06/2006
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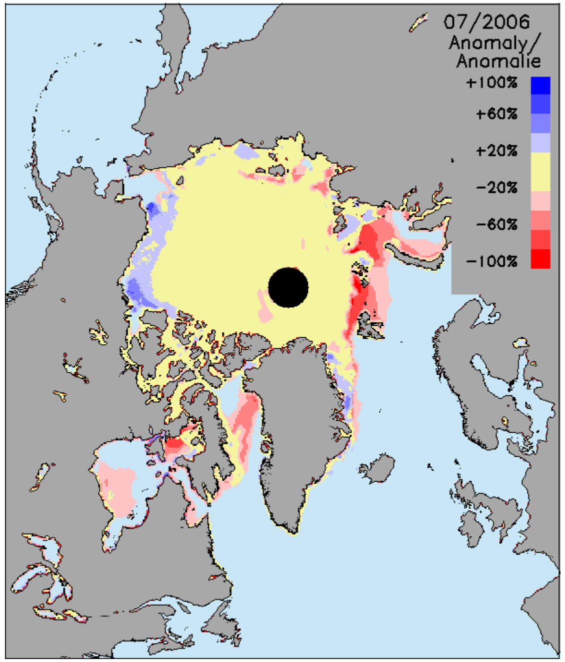
07/2006
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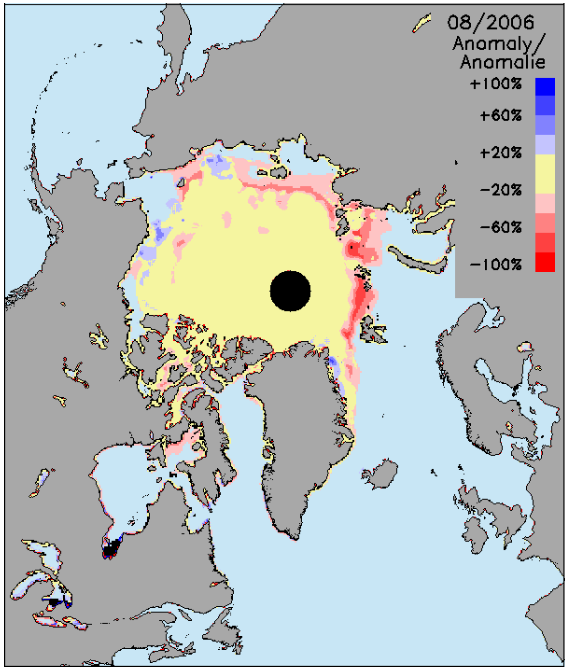
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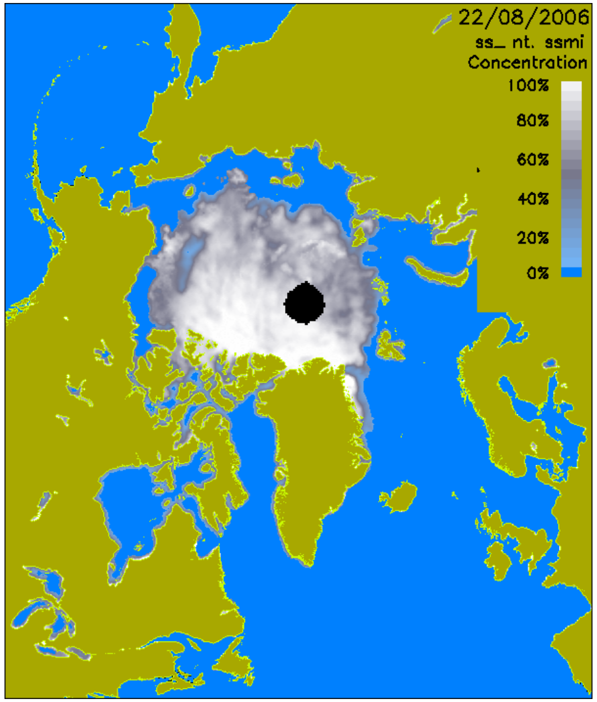
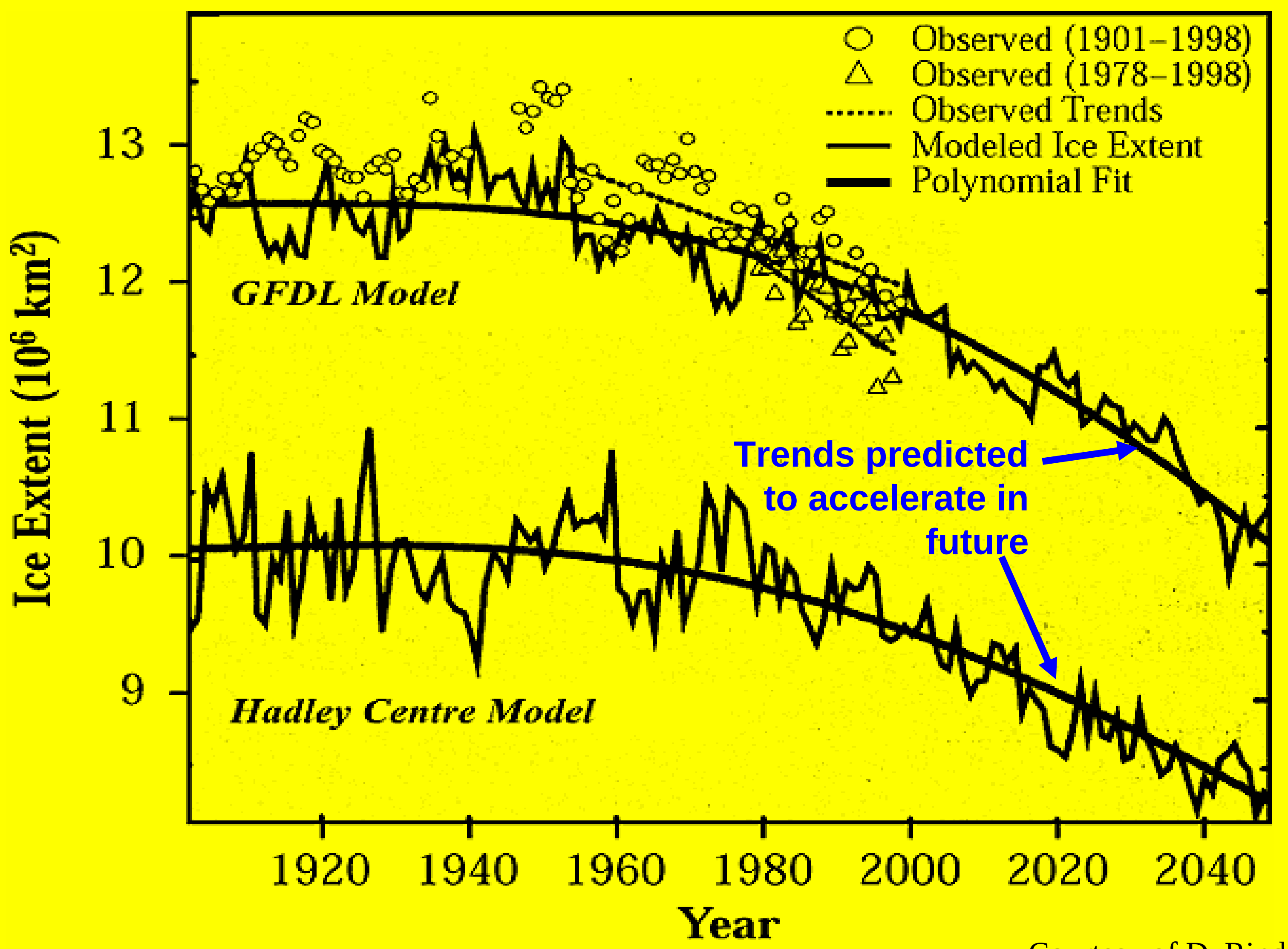
-100%

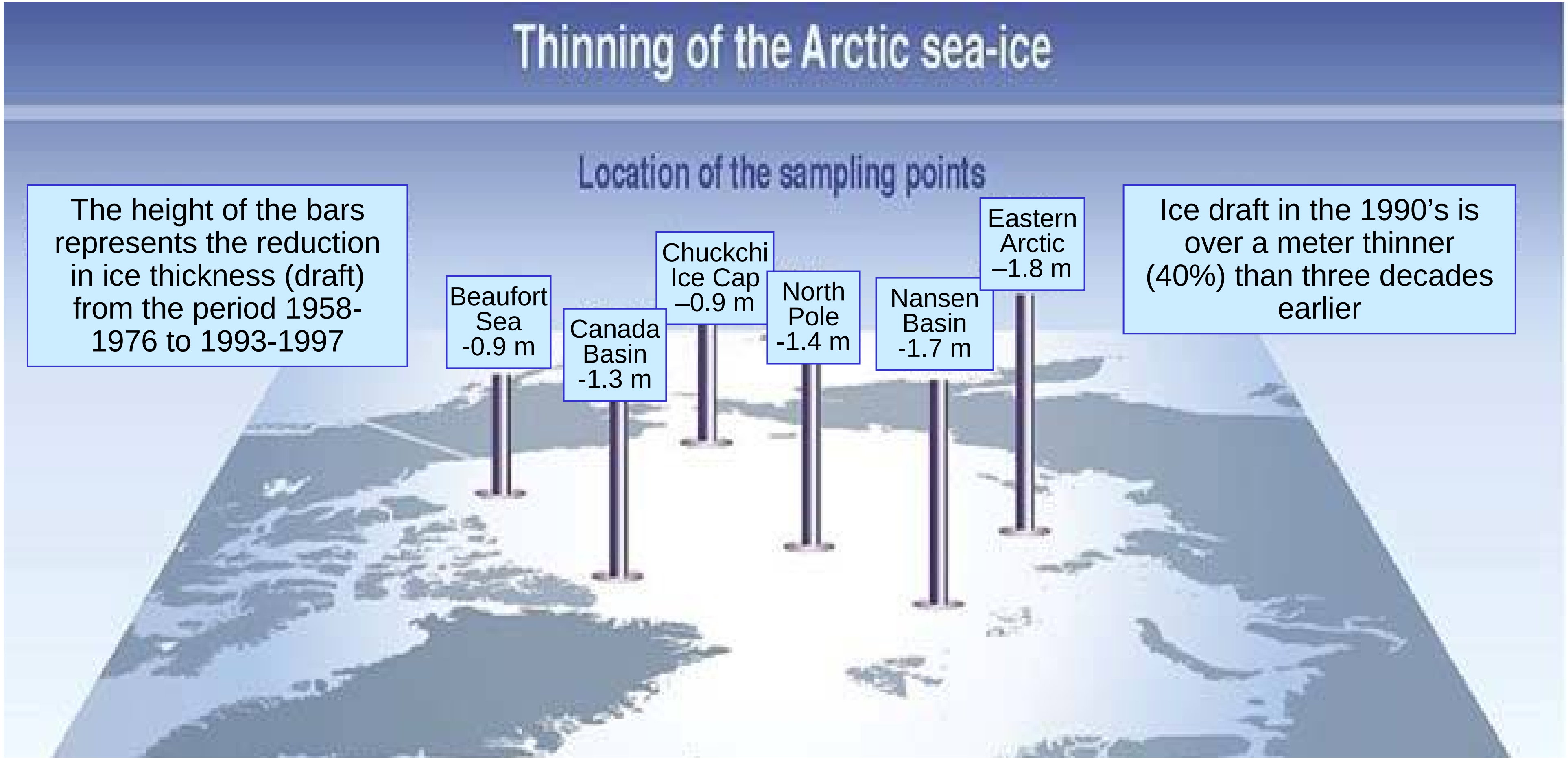

22/08/2006
ss_ nt. ssmi
Concentration
100%
80%
60%
40%
20%
0%

Modeled Sea Ice cover: 1900 - 2050



Courtesy of D. Rind at GISS

Submarine Measurements of Sea Ice Thinning

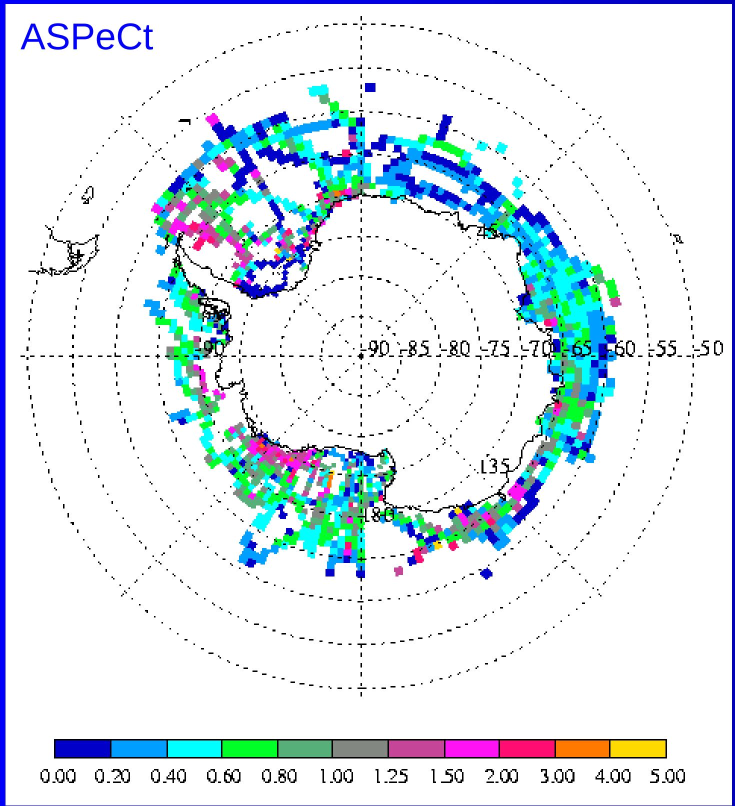


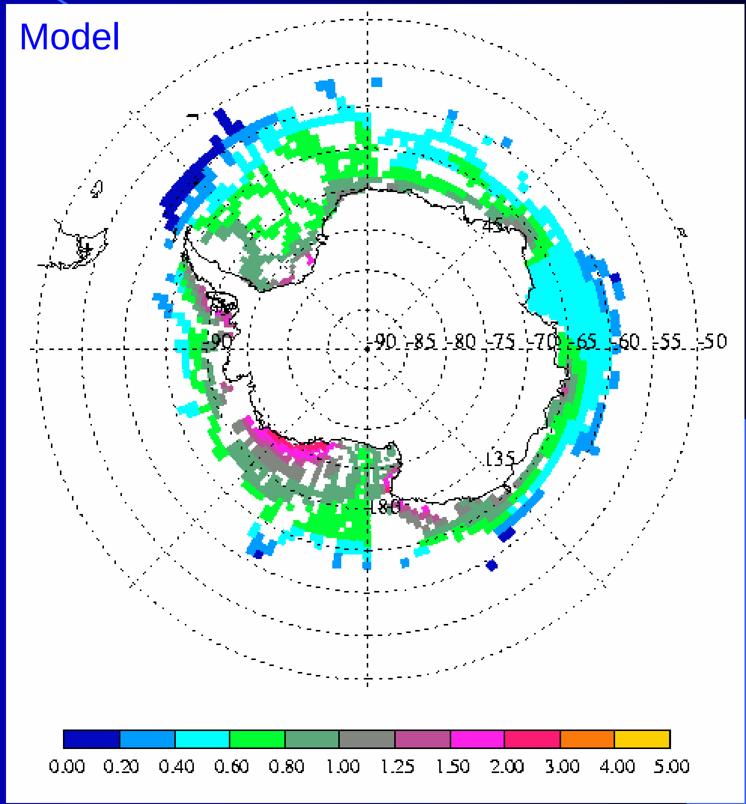
Spatial sampling?

Temporal sampling?

Sea Ice Thickness

Comparison of mean ASPeCt ice thickness with model thickness





- Small scale variability is not present in the model
- On the larger scale:
  - East Antarctic (thin ice of about 50 cm)
  - Ross Sea (thickest ice in southeast, thin ice along 180º)
  - Biggest discrepancies in the northwest and southwest Weddell Sea

Future:
Integration of other data sources
Sea Ice Reanalysis

Coutesy: Tony Worby

Summary of activities

Field campaign “ARISE” on Aurora Australis

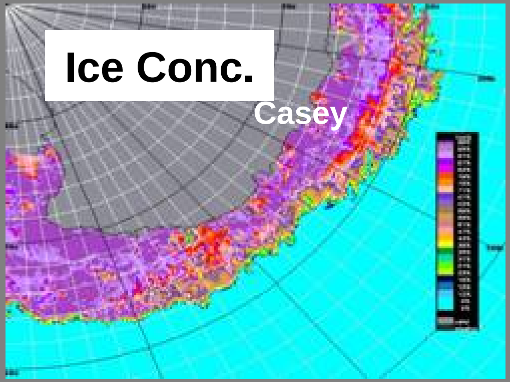
Lagrangian drift experiment for 30 days
September – October 2003
112 – 119°E; 64 – 65°S

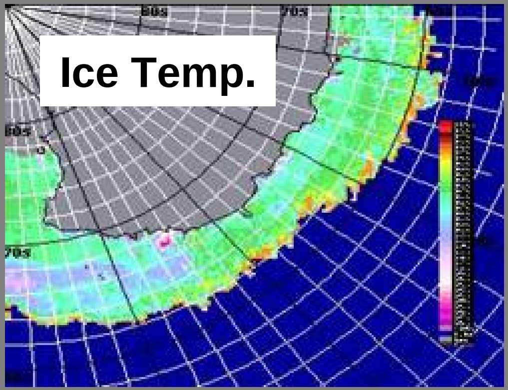
Objective of validating key products
from AMSR-E:

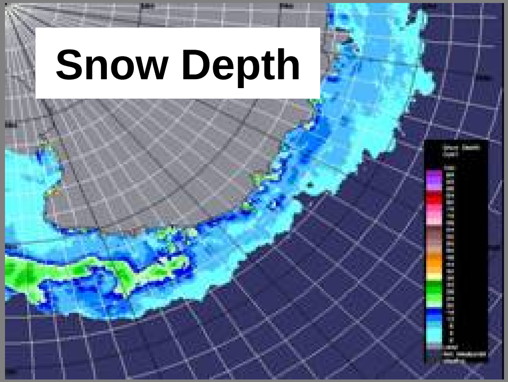
1. Ice concentration (12.5/25 km res; daily)

2. Ice Temperature (25 km res; daily)

3. Snow cover depth (12.5 km, 5 day avg)



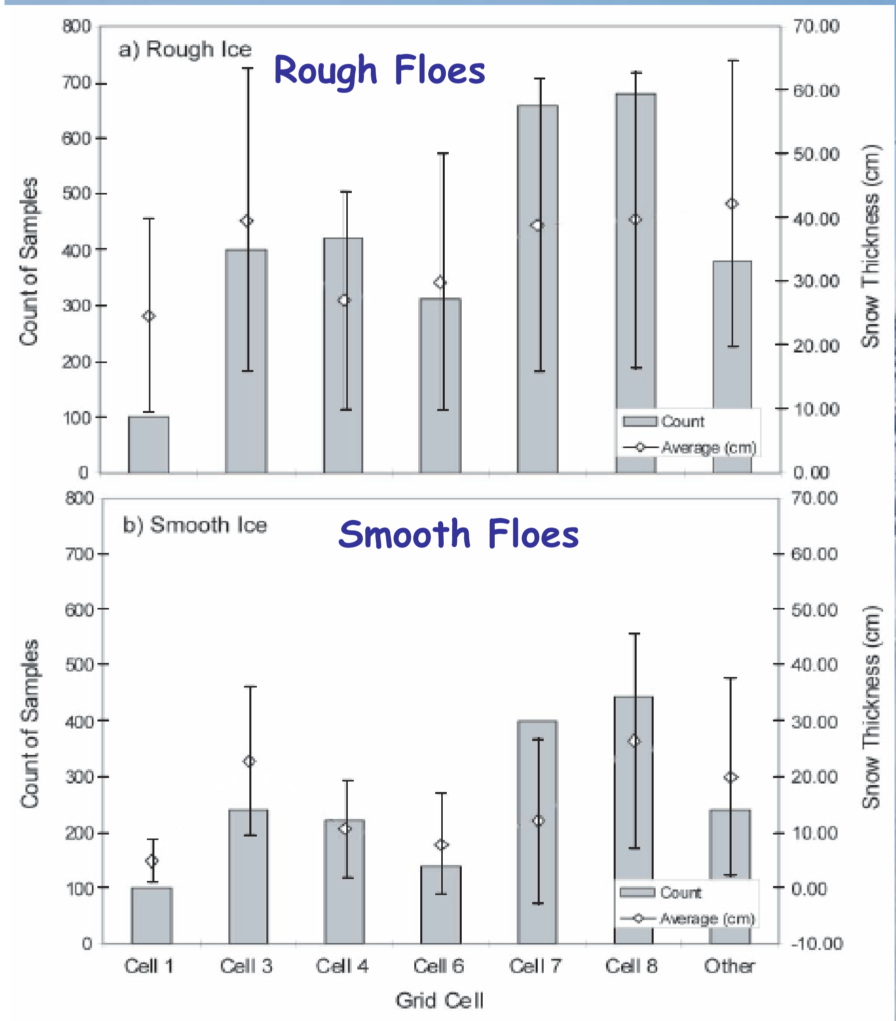




Courtesy NASA

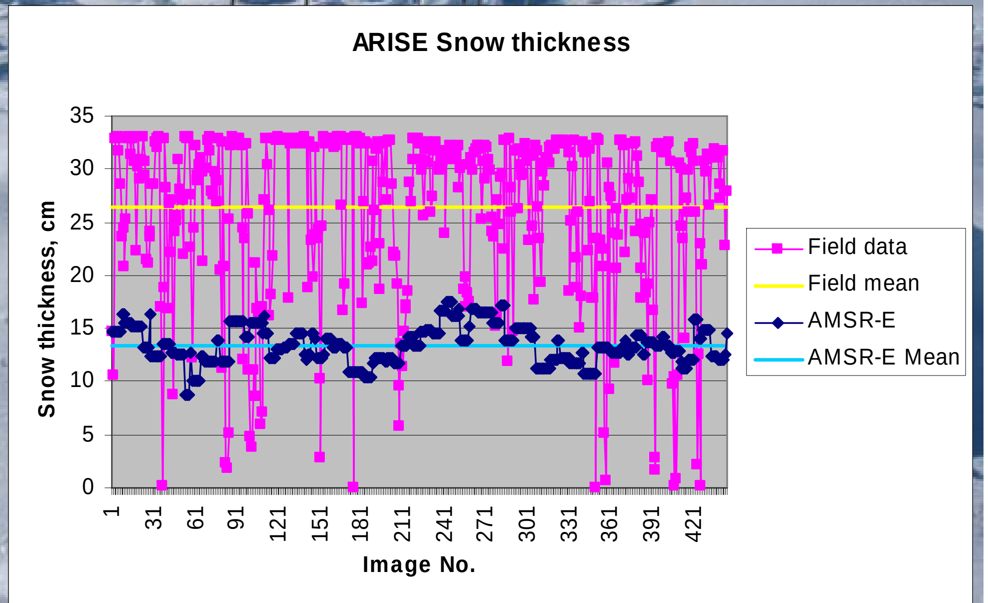
In situ snow thickness measurements were made at random locations accessed by helicopter “floe hopping” around the study region

Snow thickness for
2 Ice Classes (n = 4281)



Rough snow: 0.33 m

Smooth snow: 0.16 m



AMSR data (blue) + In situ data (pink)

GOALS of CliC Project Area 4 - Links Between the Cryosphere and Global Climate

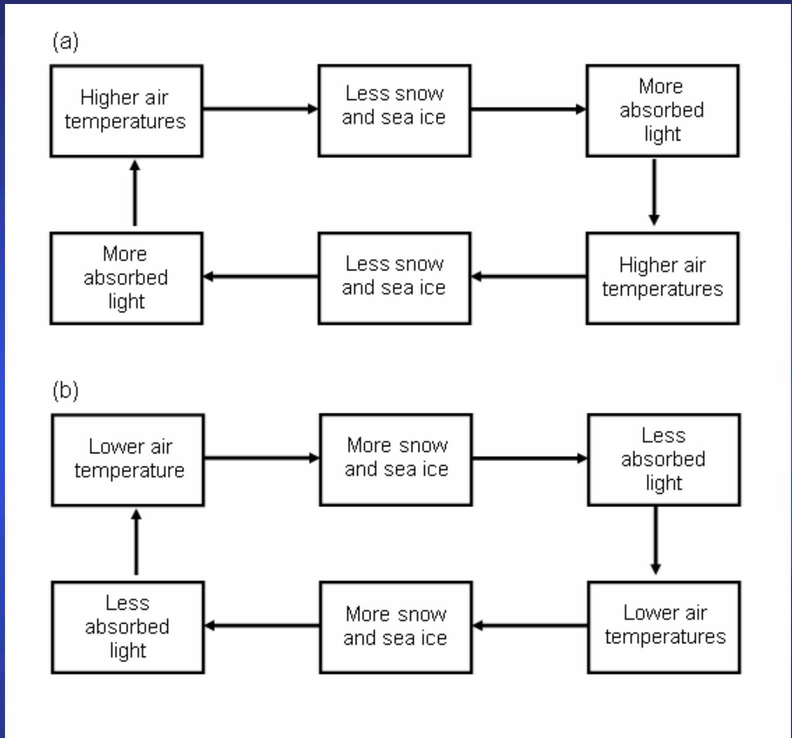
- To understand the two way interactions (radiative, thermal, hydrological and chemical) between the cryosphere and the atmospheric and oceanic circulations

- To determine the likelihood of abrupt climatic/Earth system changes resulting from processes involving the

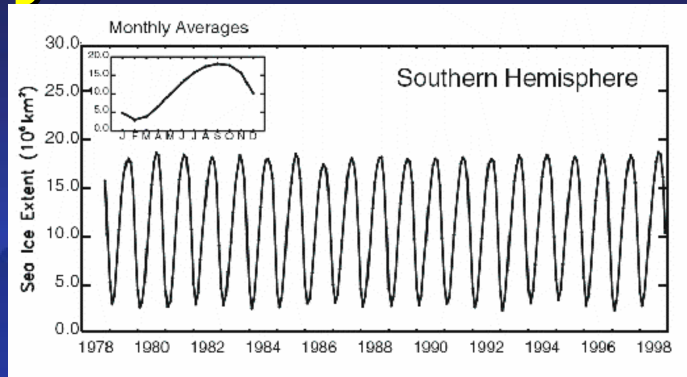
SCOPE

- Global i.e. the other CPAs have a general focus on regional to microscale processes.
- Timescale of the start of the Pleistocene, through the instrumental to the next millennium
- Highly cross-disciplinary i.e. linking the variability and change of the cryosphere to ocean and atmospheric circulation, and biogeochemical cycles

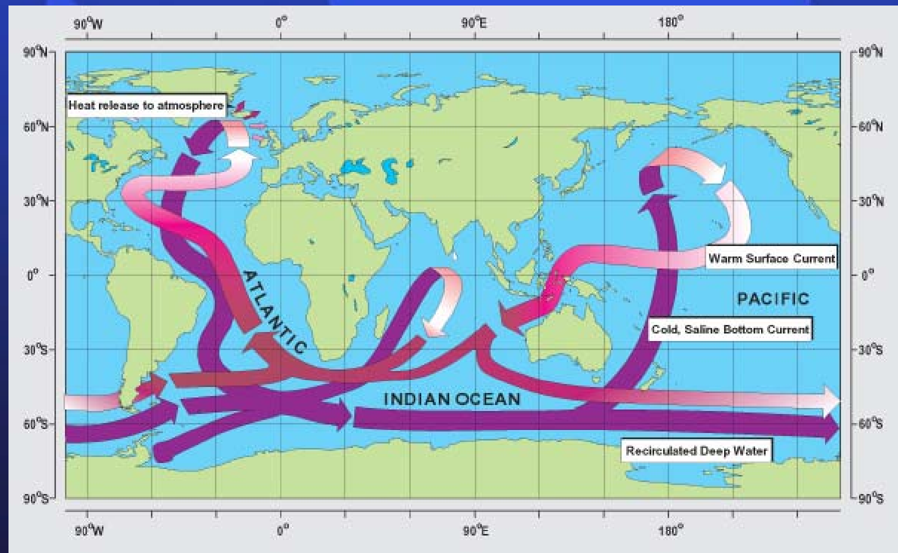
Theme 1- Mechanisms Linking the Cryosphere and the Rest of the Earth's Climate System



Ice-albedo mechanism

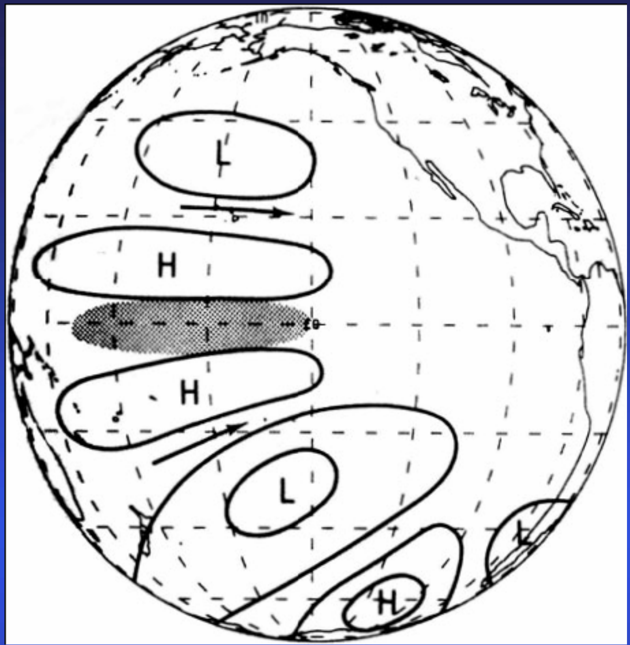


Decadal time scale variability of sea ice

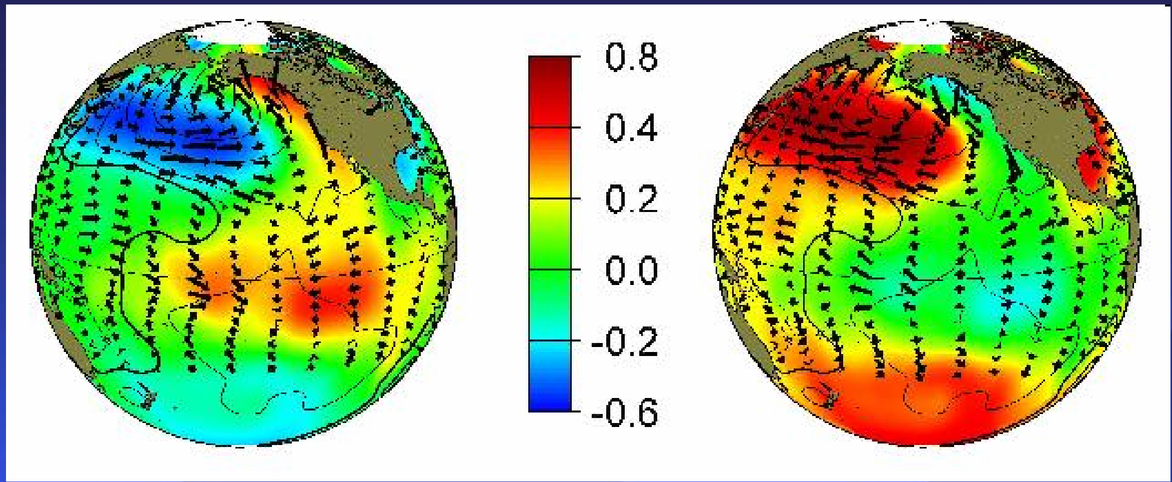


Sea ice/ice shelf links with the THC

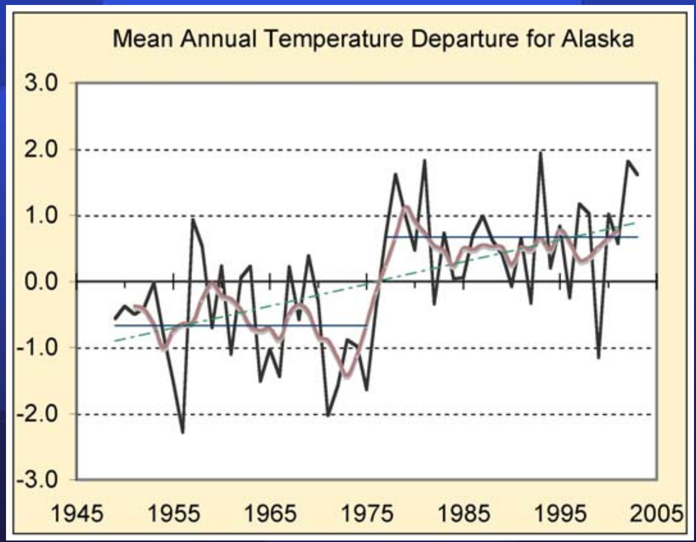
Theme 2- Global Teleconnections



Rossby wave trains links El Nino events and sea ice in the Bellingshausen Sea

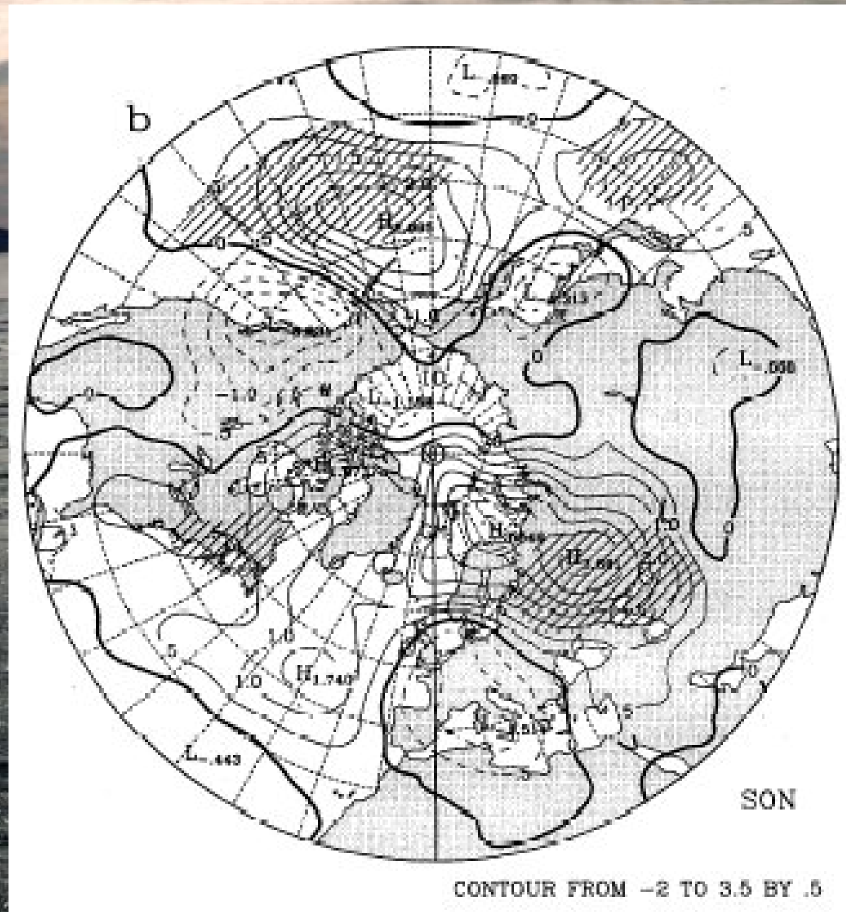


The Pacific Decadal Oscillation and Alaskan temperatures, affecting snow cover and permafrost

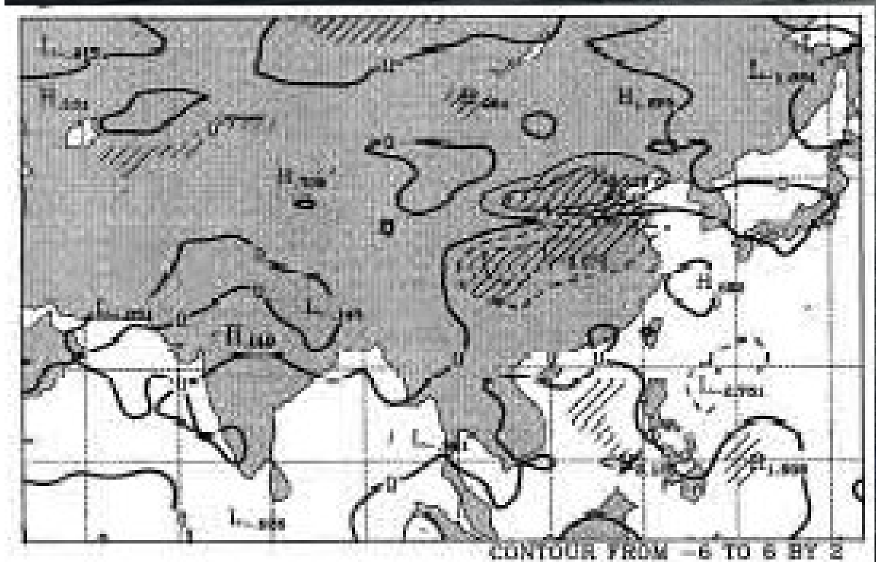


Global Implications of Reduced Antarctic Sea Ice

Model experiments with reduced Antarctic sea ice show pressure and precipitation changes in both hemispheres, including a delay in the onset of the winter monsoon over northern China in September



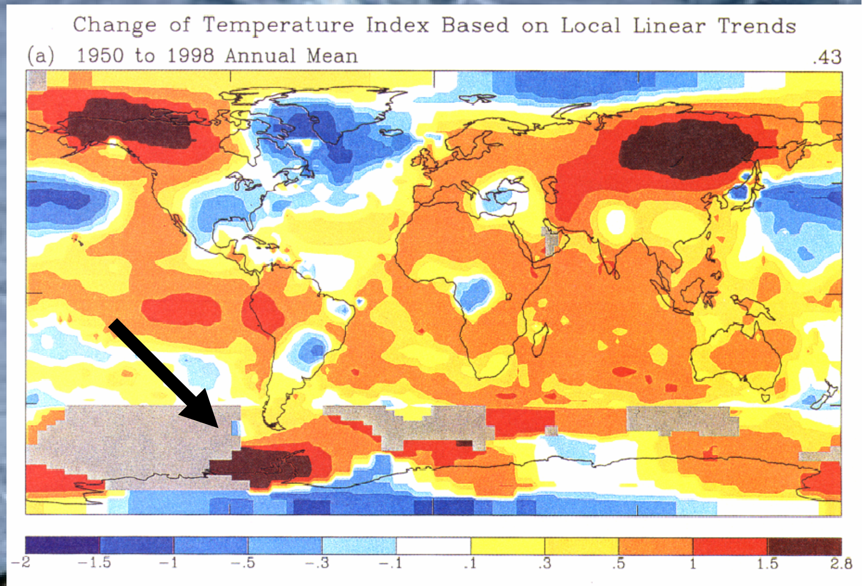
Northern Hemisphere surface pressure anomalies when Antarctic sea ice is reduced. From Bromwich et al., 1998

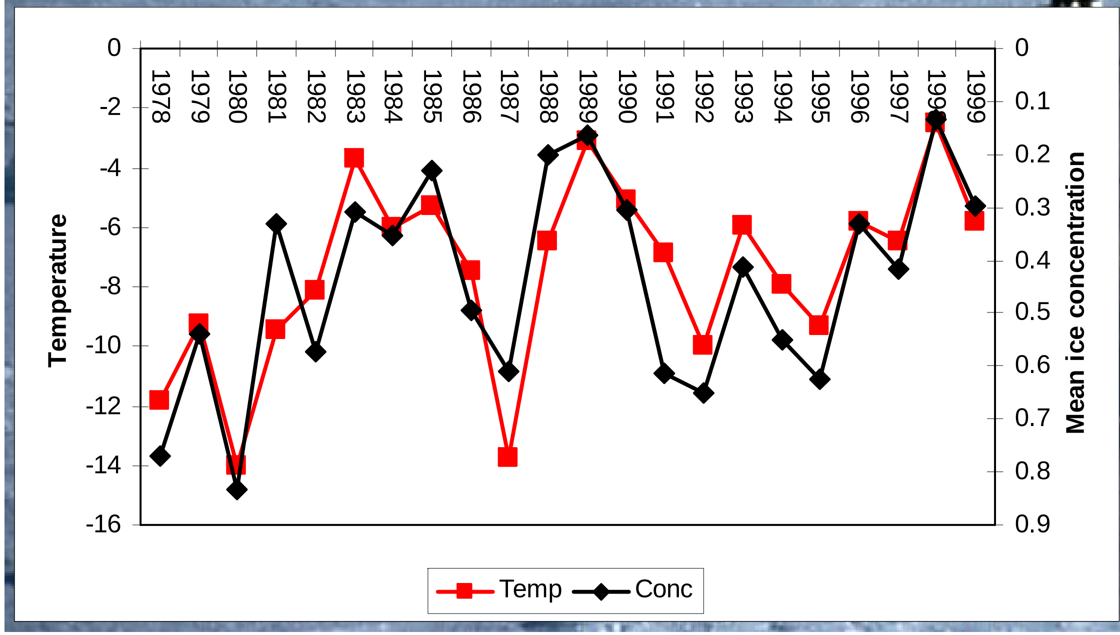


Anomalies of September precipitation with reduced Antarctic sea ice

Increasing Winter Temperatures on the Western Side of the Antarctic Peninsula Linked to a Reduction of Sea Ice

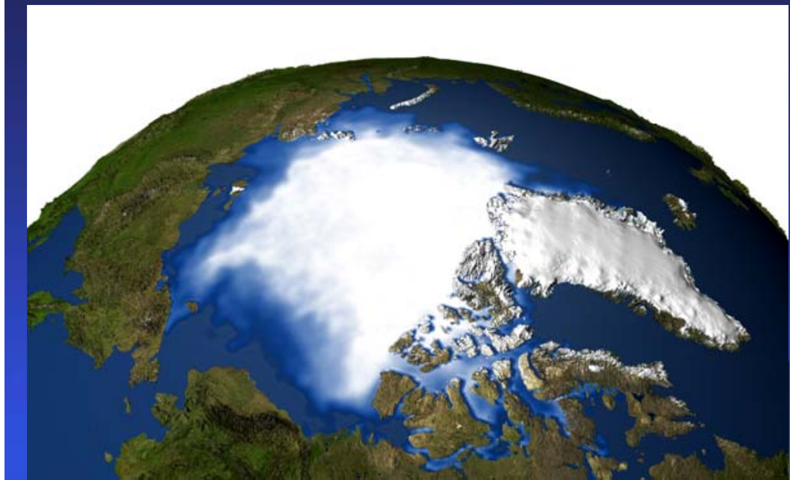
Temperatures on the Antarctic Peninsula have increased more than anywhere else on Earth over the last 50 years. This has taken place as the sea ice has reduced at a rate of -13 x 10**3 km per year over 1979-98 (Zwally et al., 2002)





The close association between temperature and ice off the coast in the Antarctic Peninsula.

Theme 3- Natural and Anthropogenic Changes in the Cryosphere



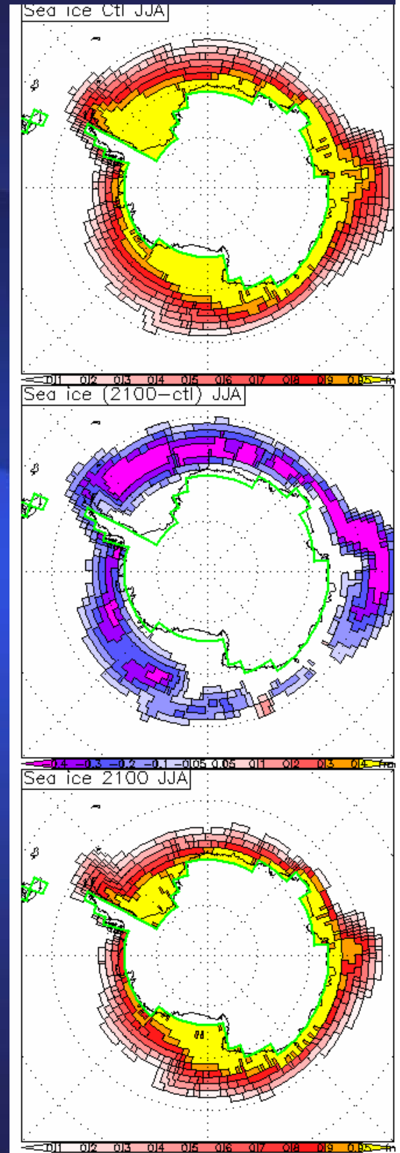
Record sea ice minima in the Arctic

Modelled Antarctic JJA sea ice

CONTROL

2100 – CONTROL

2100



TOOLS AND OTHER REQUIREMENTS FOR CPA 4

- A sustained global climate observing system capable of resolving the cryospheric-global climate linkages
- Models – GCMs, Regional Models, models of intermediate complexity
- Re-analysis fields – atmosphere, ocean, cryosphere

Cryosphere – an Indicator of Change

- The cryosphere is not only an integrator of processes within the climate system, but also an indicator of change in that system.

- Cryospheric signatures of climate change are strong because of the nature of the melt process.

Indicators:

- sea-ice extent, concentration, and thickness distribution

- change in date of beginning or end of continuous snow cover; change in number of days of continuous snow cover;

- change in date of onset of spring melt; change in frequency of the number of melt events during the winter season;

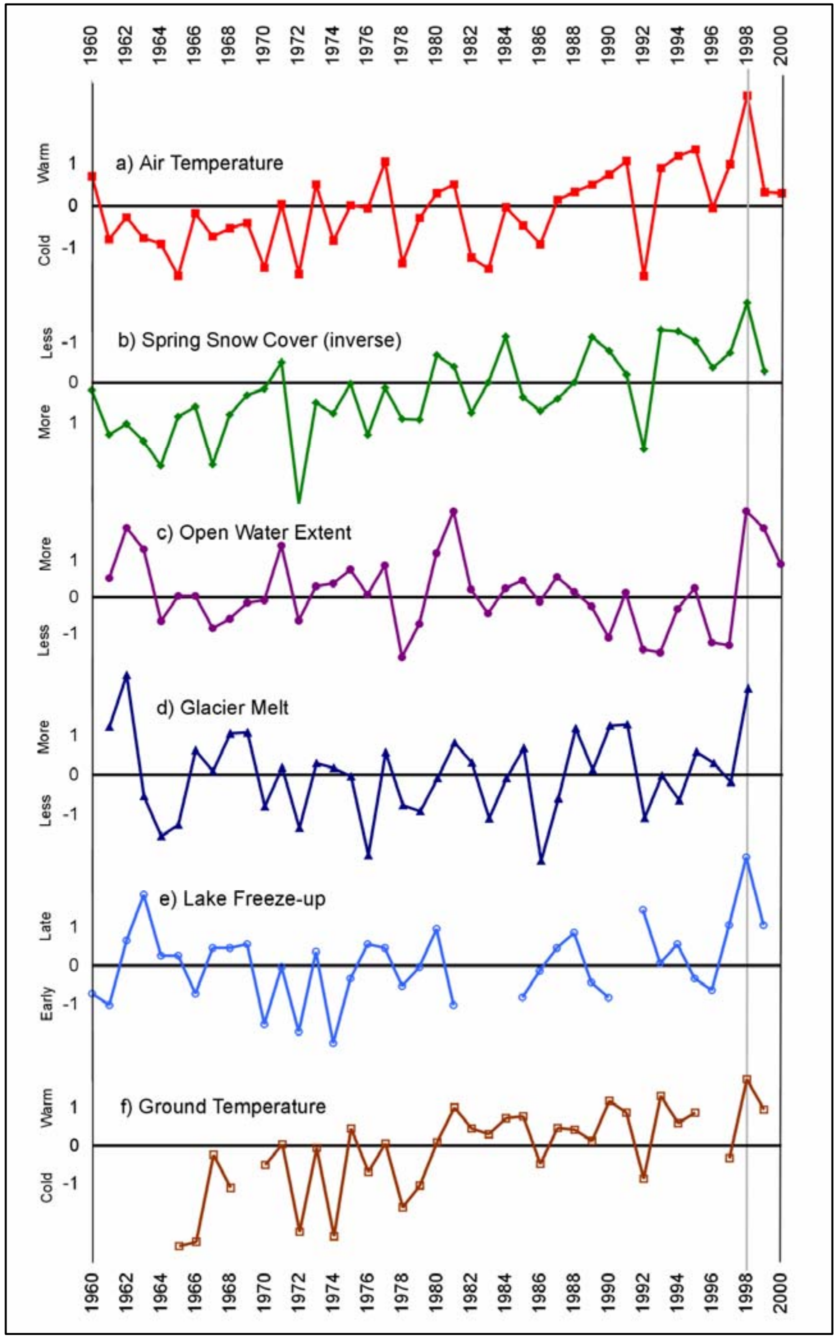
- change in snow water equivalent at peak accumulation for selected locations; change in date of peak accumulation

- change in spatial distribution of snow cover over a region and the earth

- freeze-up and break-up dates of lake ice

- thickening of the active layer and changes in the distribution of permafrost are important indicators of warming in the Arctic.

- mass balance and extent of glaciers, ice sheet, ice shelves, ice caps



Major Accomplishments: Summer of 1998 Project

- documented **the response of the Arctic cryosphere to an anomalously warm summer**, and compared this to other warm summers in the period of record

- demonstrated the **complexity of the interactions between climate and the cryosphere** and between the various components of the cryosphere e.g. the importance of critical synoptic events in clearing ice plugs, and in controlling glacier melt

- developed a number of **important climate and cyrosphere data series in the high Arctic** for assessing climate variability and change, and for GCM validation (e.g. open water percent in QEI, regional sea ice concentration, lake ice freeze-up break-up, glacier mass balance).

- provided **new understanding of ice plug formation and break-up process**

ICARP II

Research Planning in the Context of Understanding the Arctic System in a Changing World

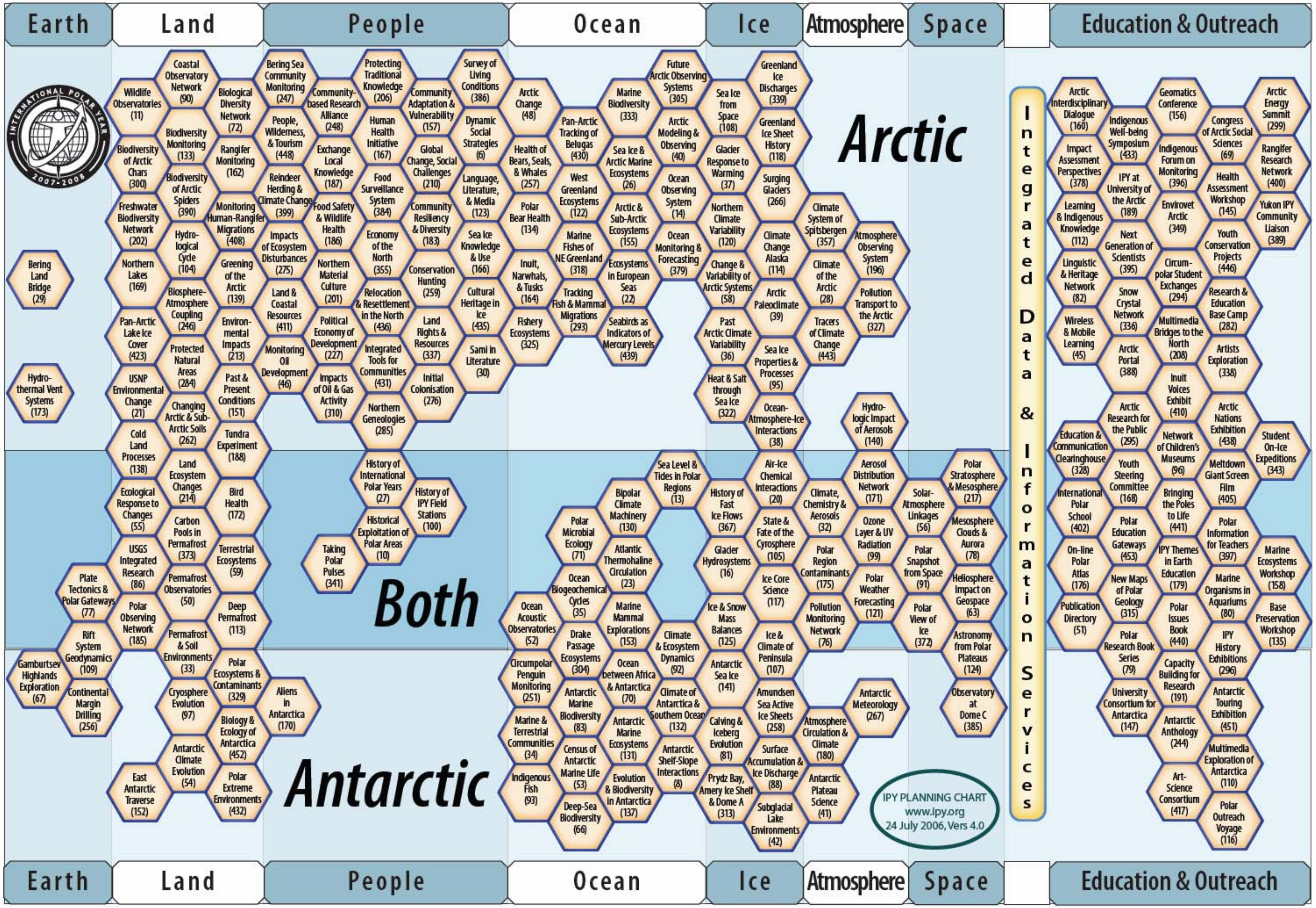
Copenhagen, November 10-13, 2005

Working Groups – Proceedings chapters

- Sustainable Development: Arctic Economies
- Indigenous Peoples and Change in the Arctic: Adaptation, Adjustment and Empowerment
- Arctic Coastal Processes
- Deep Central Basin of the Arctic Ocean
- Arctic Ocean Margins and Gateways
- Arctic Shelf Seas
- **Terrestrial Cryospheric and Hydrologic Processes and Systems (chair, Prowse)**
- Terrestrial and Freshwater Biosphere and Biodiversity
- **Modelling and Predicting Arctic Weather and Climate (chair, Bengtsson)**
- Resilience, Vulnerability and Rapid Change
- Arctic Science in the Public Interest
- Working Group on Contaminants

WCRP/CliC will seek responsibility for leading follow-on research identified in chapter 7 (key part of CPA1) and opportunity to have WCRP and WWCRP (WGNE??) take on this role for chapter 9


Research initiatives developing within the International Polar Year 2007-2008.
INTERNATIONAL POLAR YEAR
2007-2008



Earth
Land
People
Ocean
Ice
Atmosphere
Space
Education & Outreach
INTERNATIONAL POLAR YEAR 2007-2008
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IPY PLANNING CHART
www.ipy.org
24 July 2006, Vers 4.0

CliC IPY Proposal:
The State and Fate of the Cryosphere ("Cryos") Goals

In the process of enhancing our ability to measure and monitor the cryosphere, we propose to coordinate activities that will create a "snapshot" of the cryosphere and evaluate its current (IPY) state in the context of past states. We will

1. **assess the current state** of the cryospheric parameters in the polar regions,

2. **formulate the observational requirements** of cryospheric variables for weather and climate monitoring and prediction,

3. **strengthen international cooperation** in the development of cryospheric observing systems.

CliC will provide over-arching coordination of smaller-scale IPY projects and national activities, both within and outside of the IPY scope (as appropriate), linking them together in a way that increases the benefit to the IPY effort. The project will not only be a key element within IPY but will also support the new Integrated Global Observing Strategy (IGOS) Cryosphere Theme, which is being developed by CliC and SCAR (Scientific Committee on Antarctic Research).

IPY 2007 2008

Deliverables

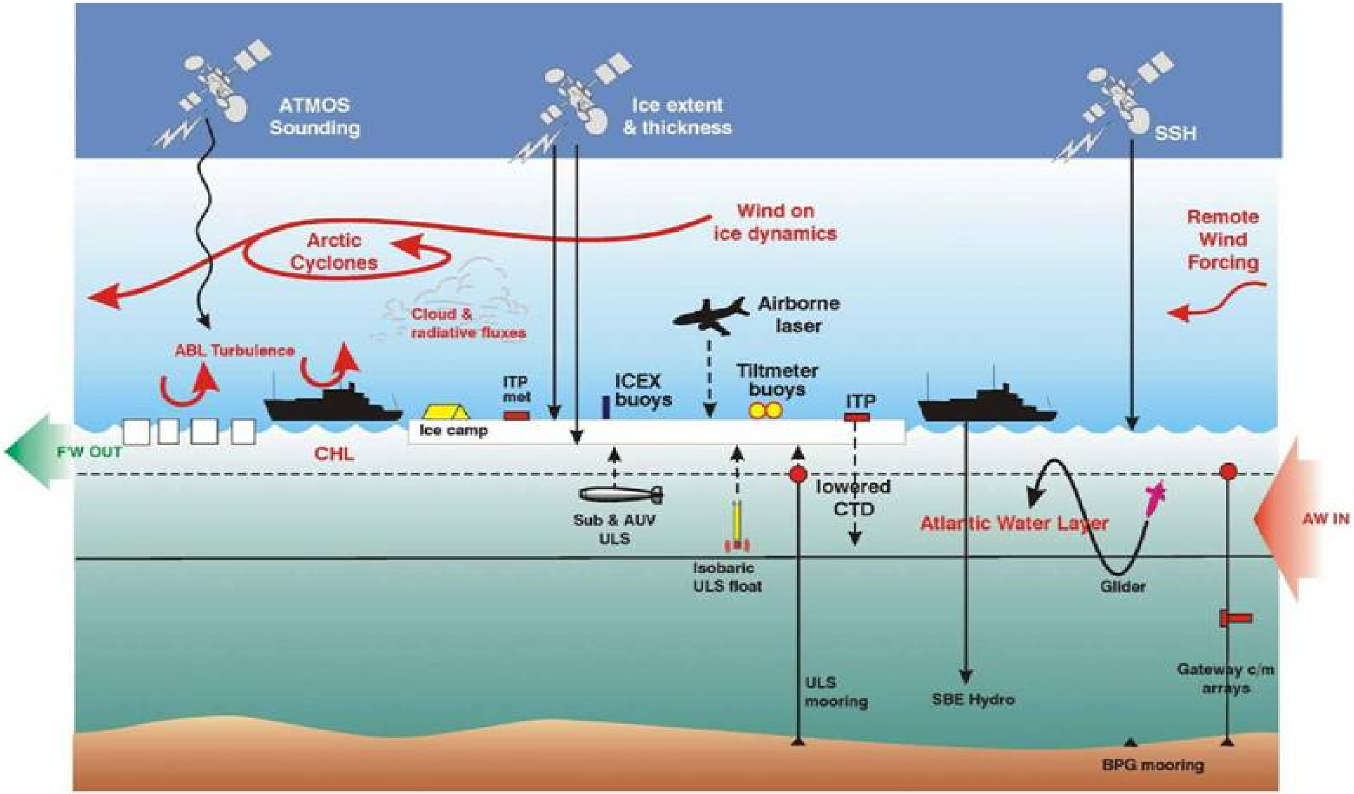
1. A **near real-time integrated product** on the current state of the global cryosphere during IPY,
2. a global, quantitative assessment of the current state of cryospheric parameters based on a **snapshot of the cryosphere** during IPY, presented in report and data set forms with estimated error bars,
3. an evaluation of the current (IPY) state of the cryosphere in the **context of past states** through comparison with existing data, providing a benchmark for future evaluation,
4. a detailed compilation of the **observational requirements** of cryospheric variables for weather and climate monitoring, prediction and projection with an identification of gaps in the current observing system,
5. an **assessment of future** cryospheric conditions through regional and global climate modeling,
6. the **establishment of the initial elements** of the Arctic Ocean and Southern Ocean observing systems and start of the implementation of the Arctic HYCOS project,
7. the establishment of multidisciplinary "**supersites**" that would include cryospheric observations in their set of measurements with CEOP as main means for data integration,
8. an assessment of **cryospheric-climate linkages and feedbacks** that can be used to understand and explain the observed cryospheric variability and change,
9. an assessment of the **ecological and human implications** of the observed/predicted changes.

WMO OMM

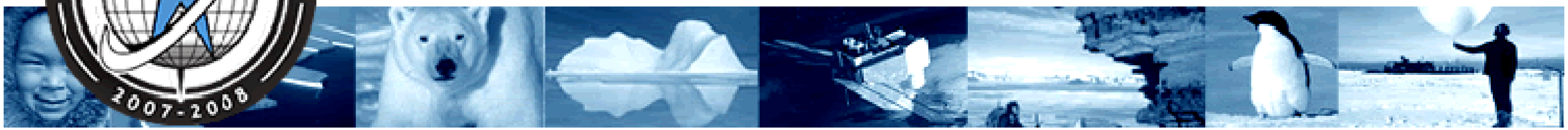
Integrated Arctic Ocean Observing System (iAOOS)

8 nations: 54 EoIs

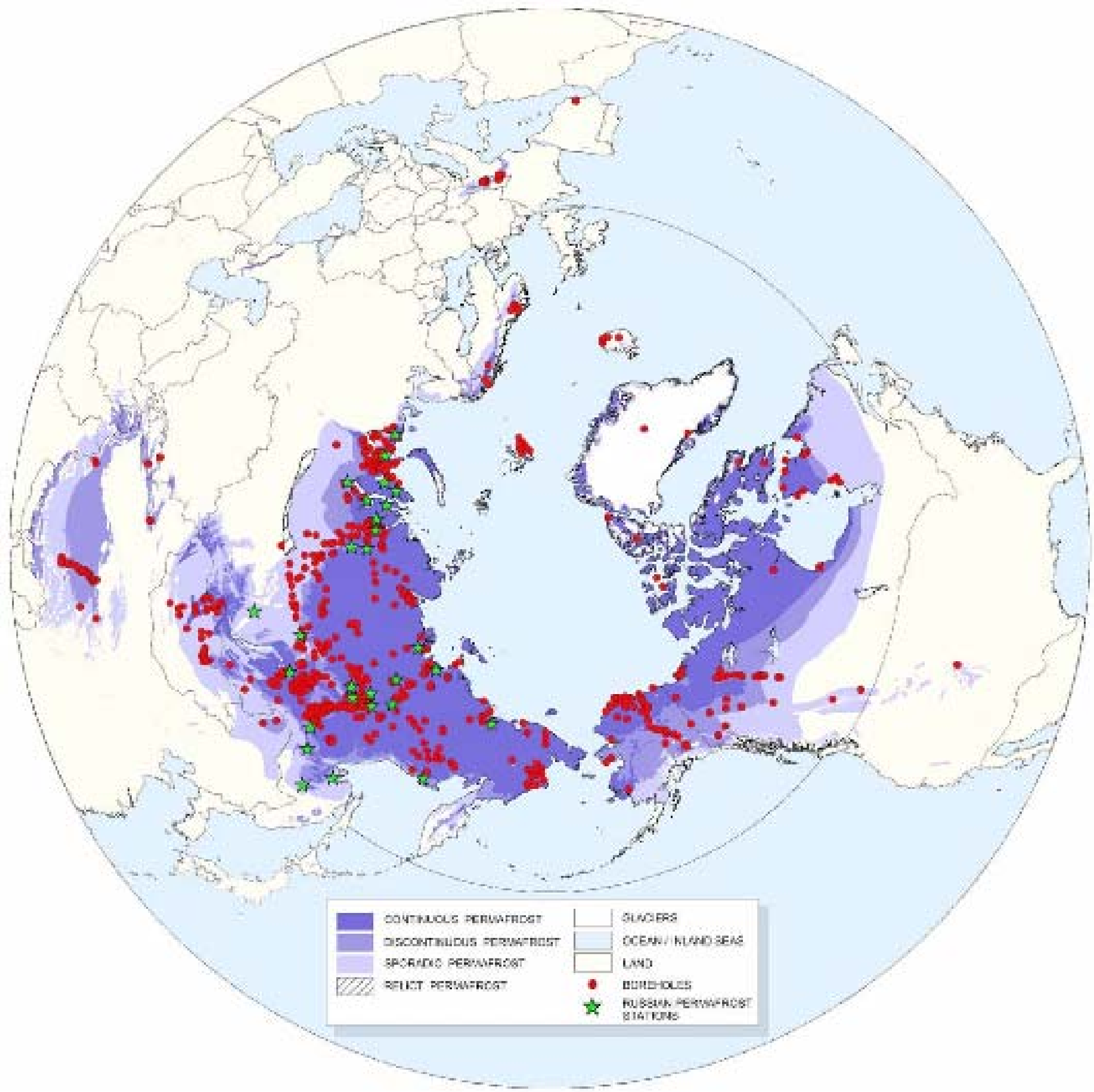
Observing the Arctic Ocean from satellites to sea bed



Vertical transect through the Arctic Ocean: iAOOS from satellites to seabed



IPY Project 50: Thermal State of Permafrost (TSP)
Jerry Brown, International Permafrost Association



Some other related major IPY activities

- DAMOCLES (EU)
- SEARCH (USA)
- ISAC (International Study of Arctic Change)
- Sea ice mass balance for Arctic and Antarctic
- BEARDS (sea ice drifting buoy program)
- CRAC (processes of iceberg calving)
- Southern Ocean programs CASO, SASSI
- Many activities within national programs…

CPA 4 ACTIVITIES IN IPY

- *Case studies of tropical-cryospheric links*
- *Development and testing of models*
- *Production of very high quality analyses*
- *Investigation of bipolar linkages*
- *Collection of high resolution ice cores to investigate past climate and atmospheric/oceanic circulation*

IGOS Theme on Cryosphere

Dr. Jeff Key, Chair

Theme Goals

To create a framework for improved coordination of cryospheric observations conducted by research, long-term scientific monitoring, and operational programmes;

To achieve better availability and accessibility of data and information needed for both operational services and research;

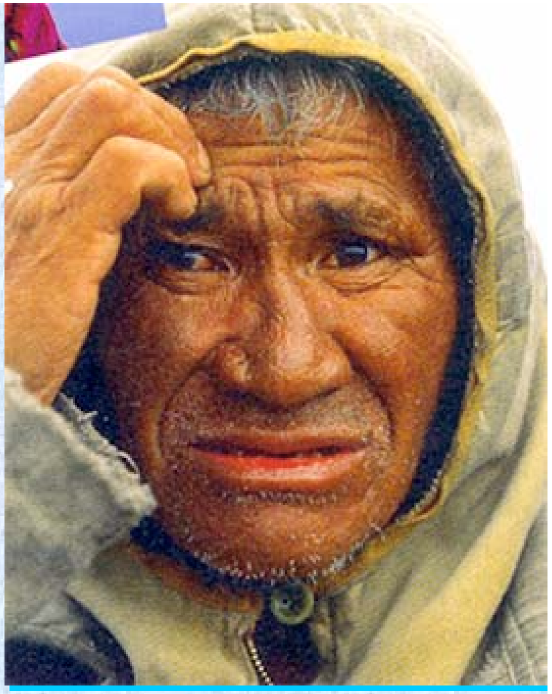
To strengthen national and international institutional structures responsible for cryospheric observations;

To increase resources for ensuring the transition of research-based cryosphere observing projects to sustained observations.

GEOSS Societal Benefit Areas and IGOS-P cryo direct linkages

- Disasters ★★
- Health ★★
- Energy ★★★
- Climate ★★★★
- Water ★★★★
- Weather ★★★
- Ecosystems ★★★
- Agriculture ★★
- Biodiversity ★

Ice, through Inuit eyes: Characterizing sea ice processes, importance and change in three Nunavut communities



Two-year community-based sea ice field research in Cape Dorset, Igloolik, and Pangnirtung, Nunavut (2003 – 2005) - 84 interviews conducted with 63 Inuit elders and hunters on:

Inuktitut sea ice terminology

- **Local freeze-thaw processes**
- **Local influences of winds and currents on sea ice**
- **Importance and uses of sea ice around each community**
- **Methods of determining sea ice safety, and sea ice navigation**
- **Map compilations of key sea ice features, dangers, routes, and changes for each community**
- **Inuit perspectives on satellite imagery and working with scientists**

- **Focus groups to link Inuktitut terminology to sea ice photos (visual learning/communication tool)**

- **Development of conceptual models of Inuit sea ice expertise (e.g. freeze-thaw processes, wind and current influences on sea ice)**

Laidler, G. J. In press. *Inuit and scientific perspectives on the relationship between sea ice and climate: the ideal complement?* Climatic Change.


Thank You