Impacts of Climate Change and Variability on Hydropower Systems in Alaska and Proving Ground Collaboration with RFC

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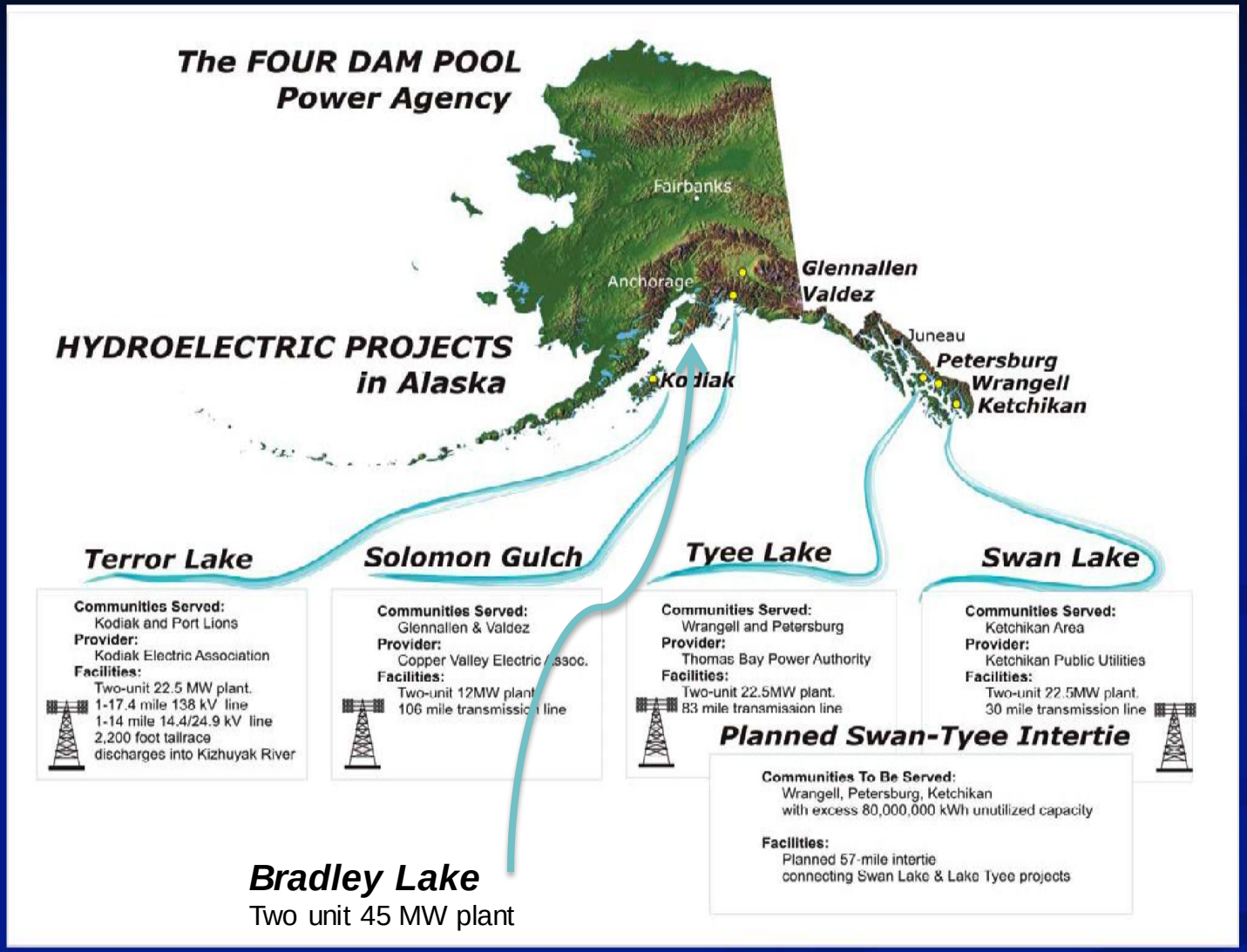
Nancy Fresco (UAF/SNAP), Sarah Trainor (UAF/SNAP/ACCAP),
Amy Tidwell (UAF/INE)

Outline

- Physical Infrastructure
- Climate sensitivity
- Impacts of climate change
- Impacts of climate variability
- High Latitude Proving Ground Snow-related activities
- Other Tools in our Toolbox/Ongoing activities


The FOUR DAM POOL
Power Agency
HYDROELECTRIC PROJECTS
in Alaska
Fairbanks
Anchorage
Glennallen
Valdez
Juneau
Petersburg
Wrangell
Ketchikan
Terror Lake
Communities Served:
Kodiak and Port Lions
Provider:
Kodiak Electric Association
Facilities:
Two-unit 22.5 MW plant.
1-17.4 mile 138 kV line
1-14 mile 14.4/24.9 kV line
2,200 foot tailrace
discharges into Kizhuyak River
Solomon Gulch
Communities Served:
Glennallen & Valdez
Provider:
Copper Valley Electric Assoc.
Facilities:
Two-unit 12MW plant
106 mile transmission line
Tyee Lake
Communities Served:
Wrangell and Petersburg
Provider:
Thomas Bay Power Authority
Facilities:
Two-unit 22.5MW plant.
83 mile transmission line
Swan Lake
Communities Served:
Ketchikan Area
Provider:
Ketchikan Public Utilities
Facilities:
Two-unit 22.5MW plant.
30 mile transmission line
Planned Swan-Tyee Intertie
Communities To Be Served:
Wrangell, Petersburg, Ketchikan
with excess 80,000,000 kWh unutilized capacity
Facilities:
Planned 57-mile intertie
connecting Swan Lake & Lake Tyee projects
Bradley Lake
Two unit 45 MW plant

SE Grid – Existing and Proposed

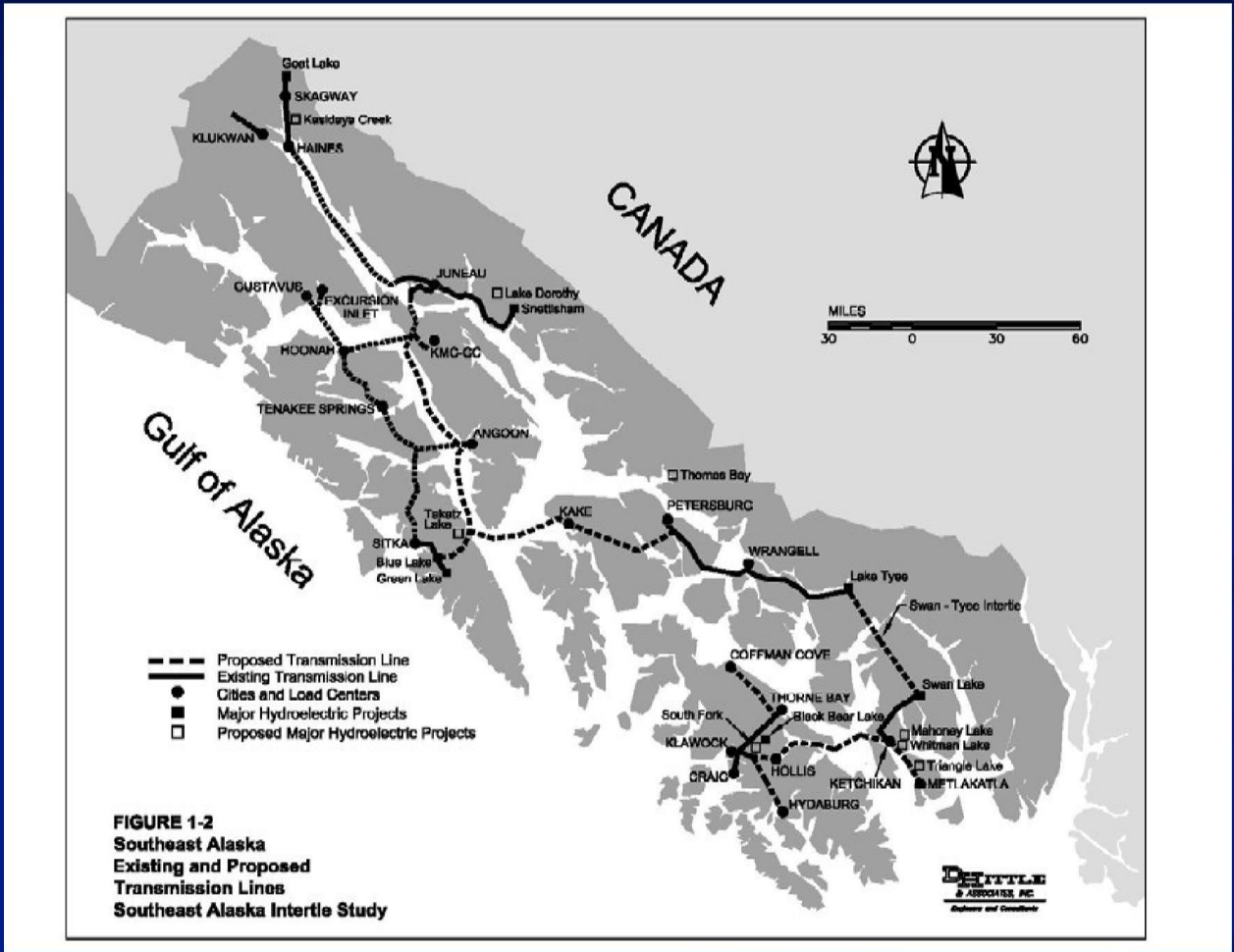
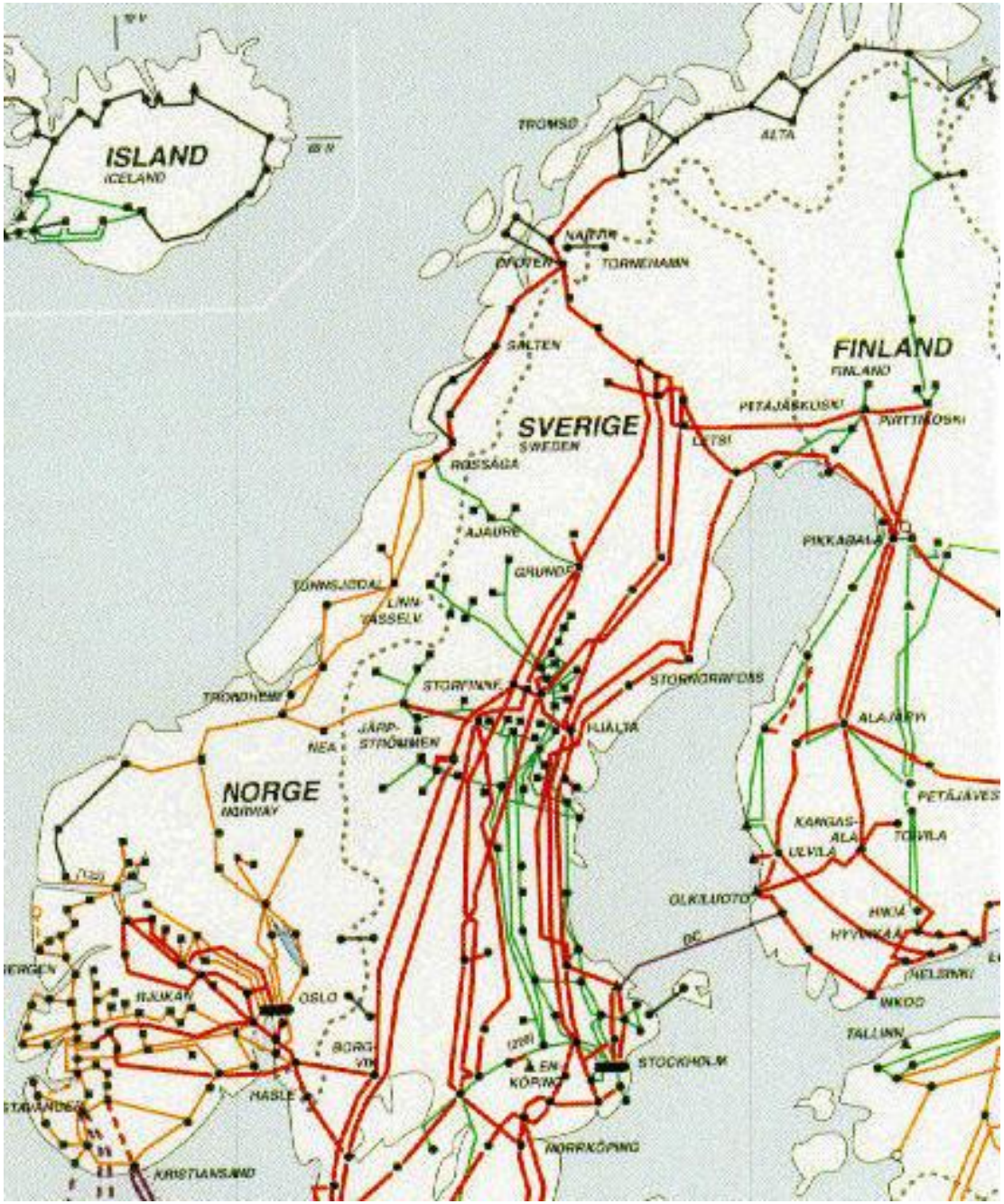


FIGURE 1-2
Southeast Alaska
Existing and Proposed
Transmission Lines
Southeast Alaska Intertie Study

The FOUR DAM POOL Power Agency

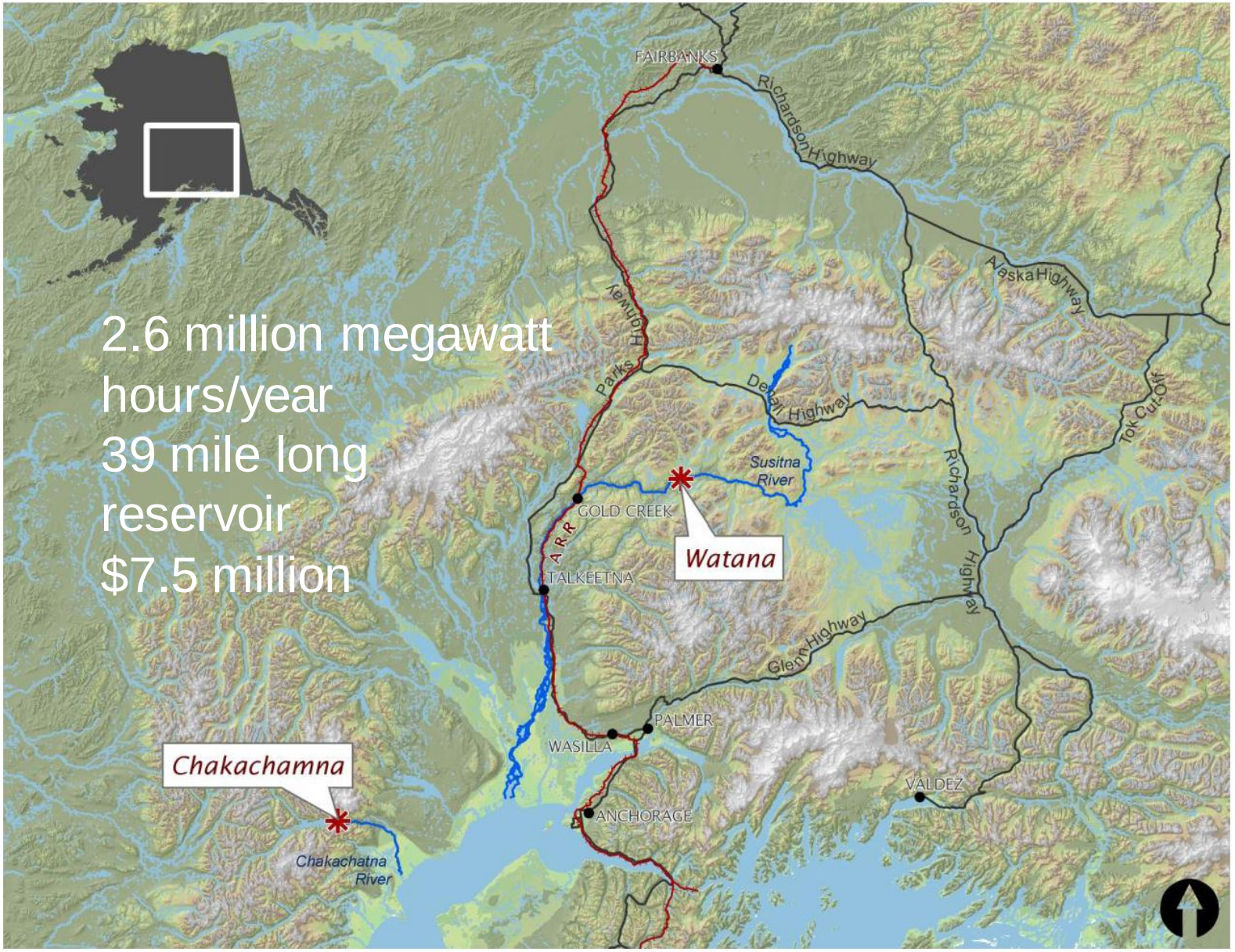
Scandinavian Electric Grid



Global Energy Network Institute

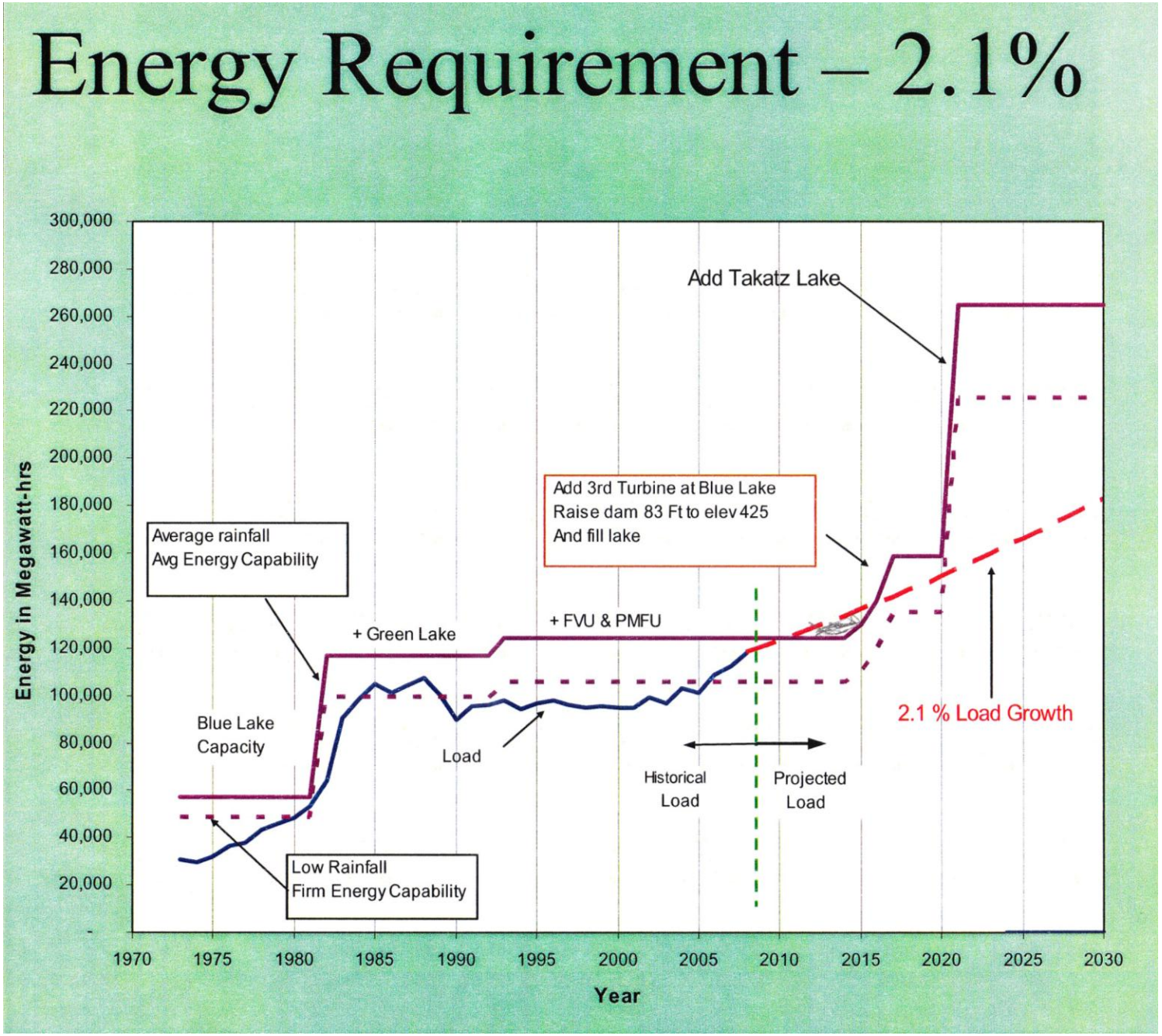
Future Development Proposed throughout Southeast Alaska and Susitna in the Railbelt

Susitna Proposal



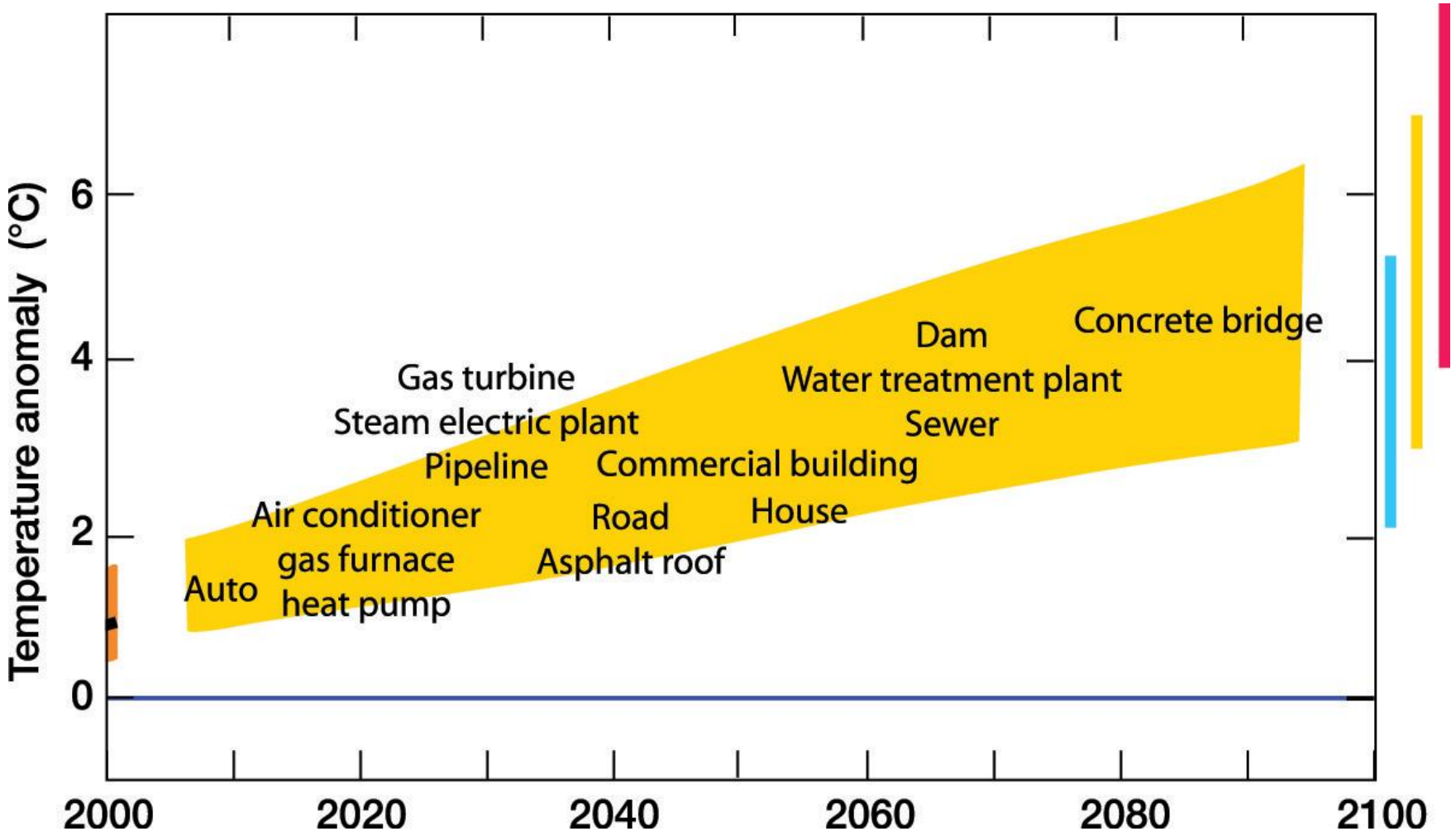
Climate Sensitivity of Hydropower Systems

Energy Requirement – 2.1%



SITKA Facilities, courtesy Chris Brewton

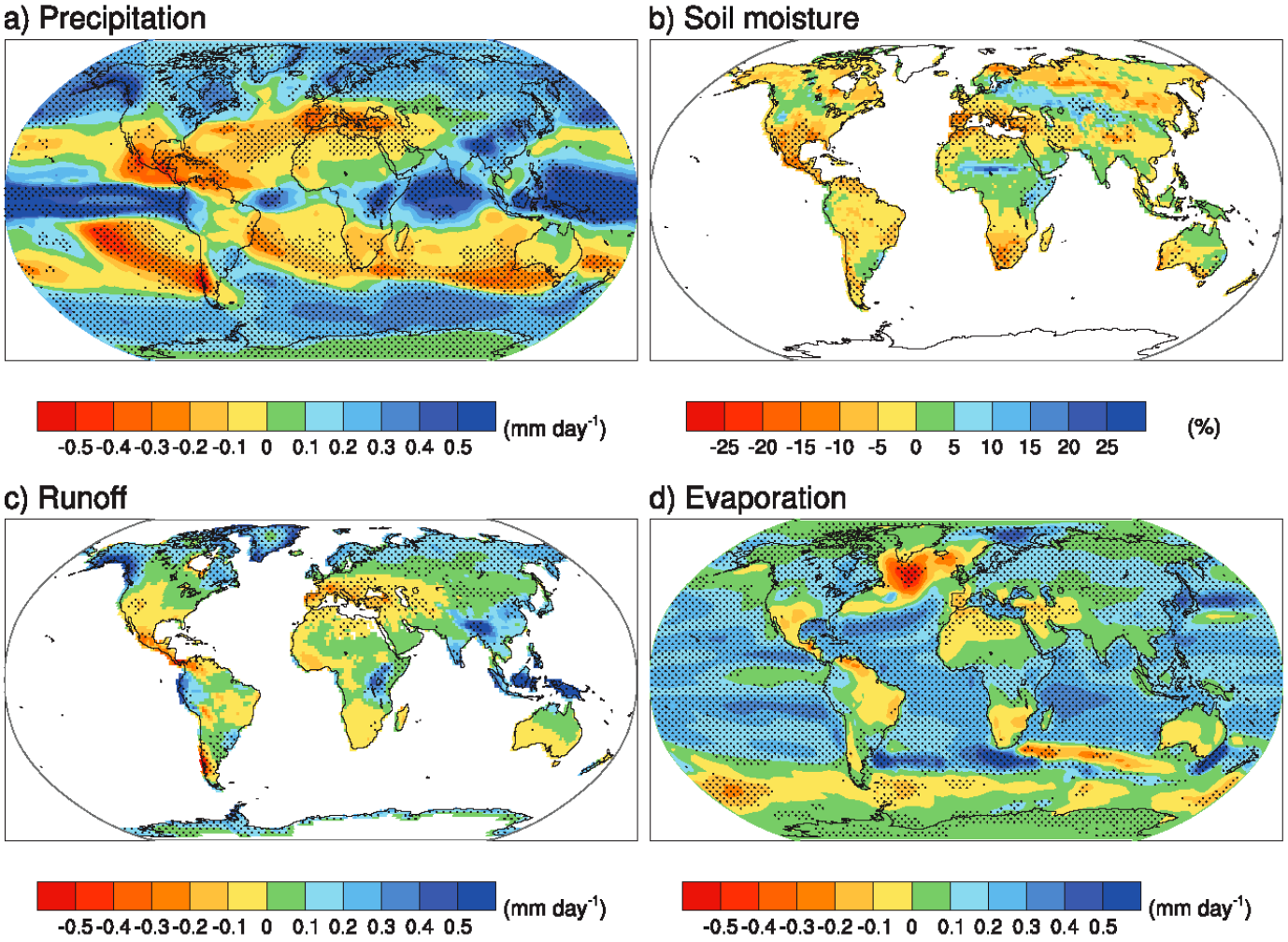
Projected temperatures and infrastructure lifespan



IPCC, 2007

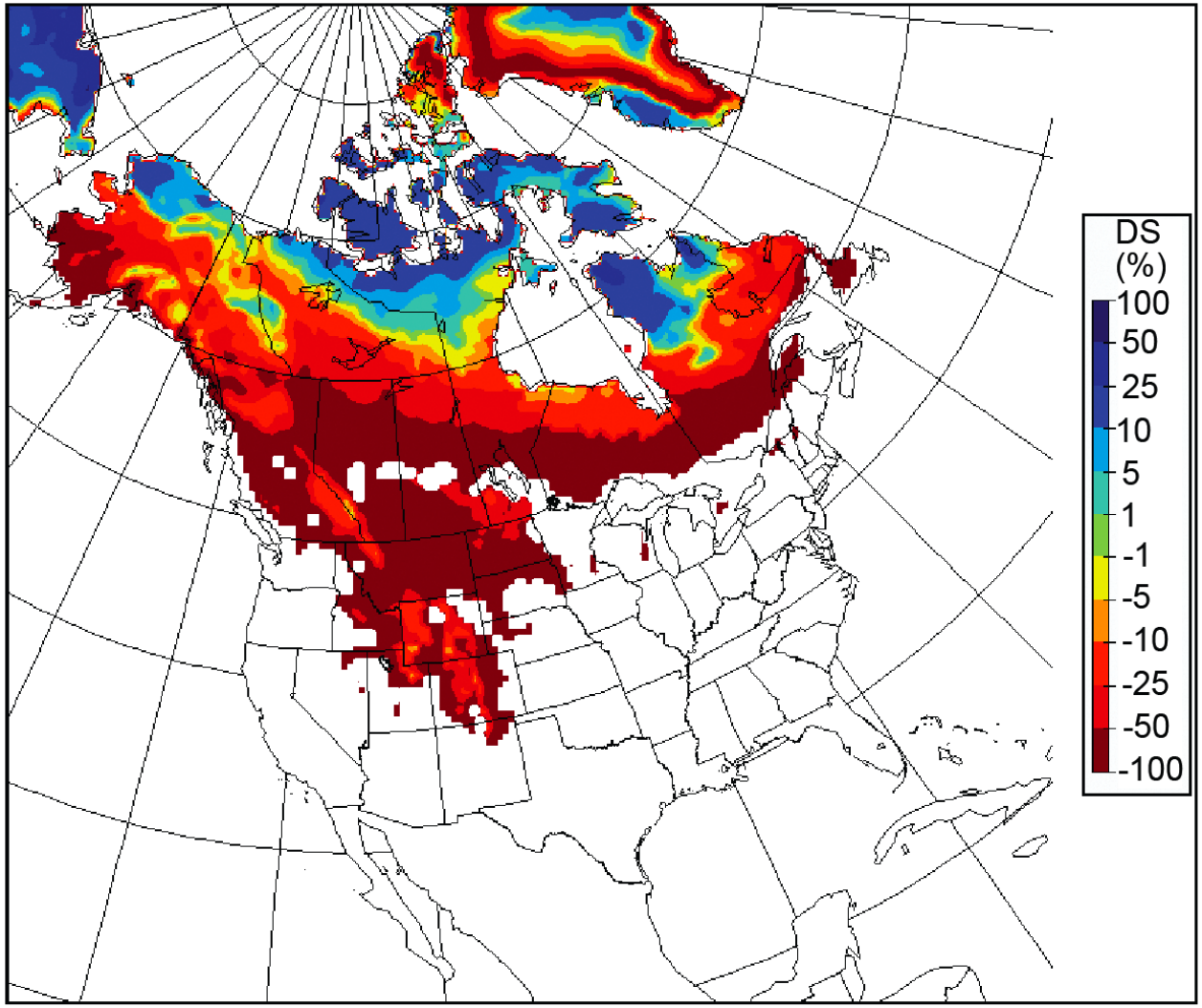
Long-term Climate Change Projections: good for hydropower

IPCC projected water cycle changes (missing permafrost, glacier feedbacks)



Meehl et al., 2007

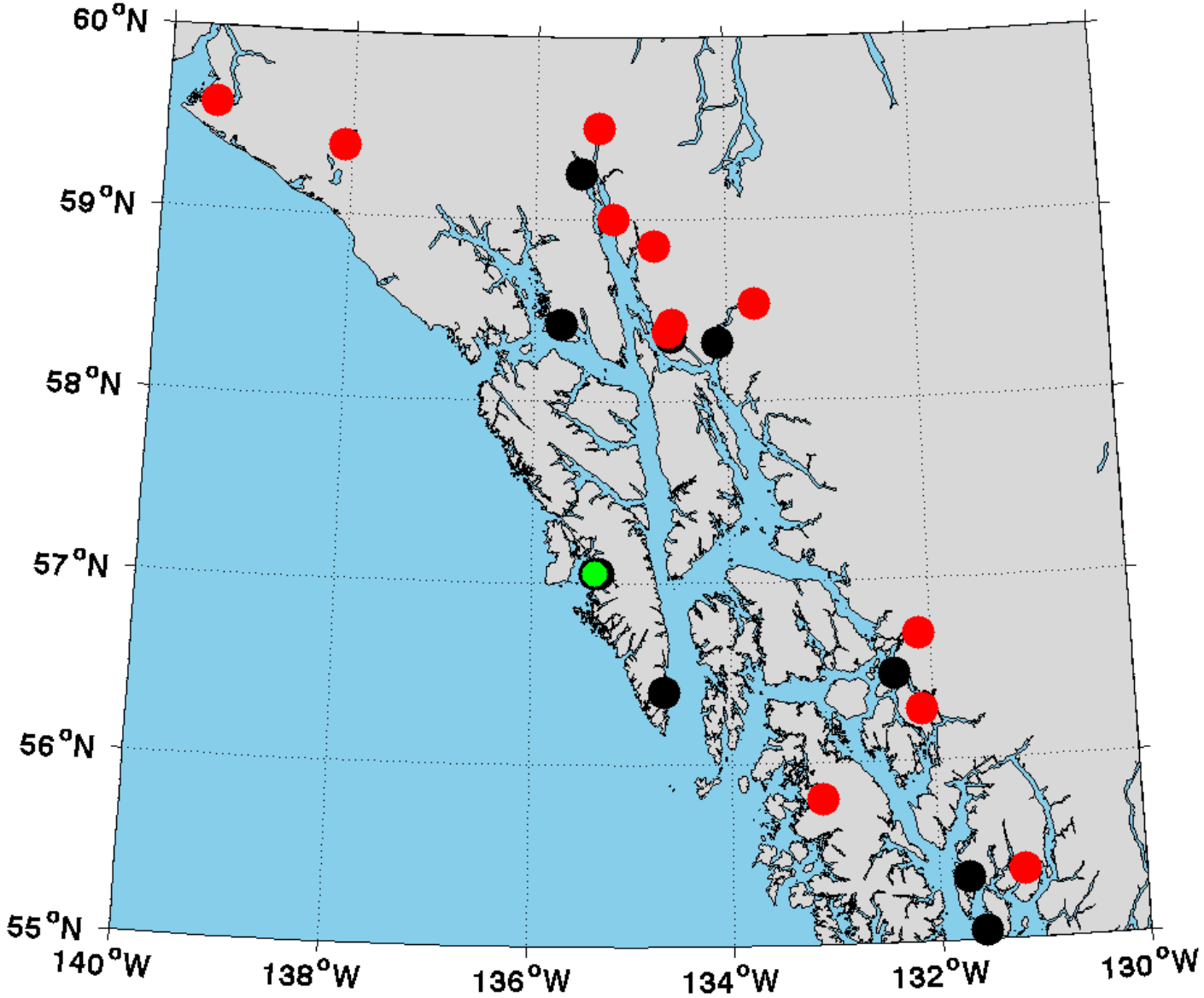
Projected spatial snow cover change



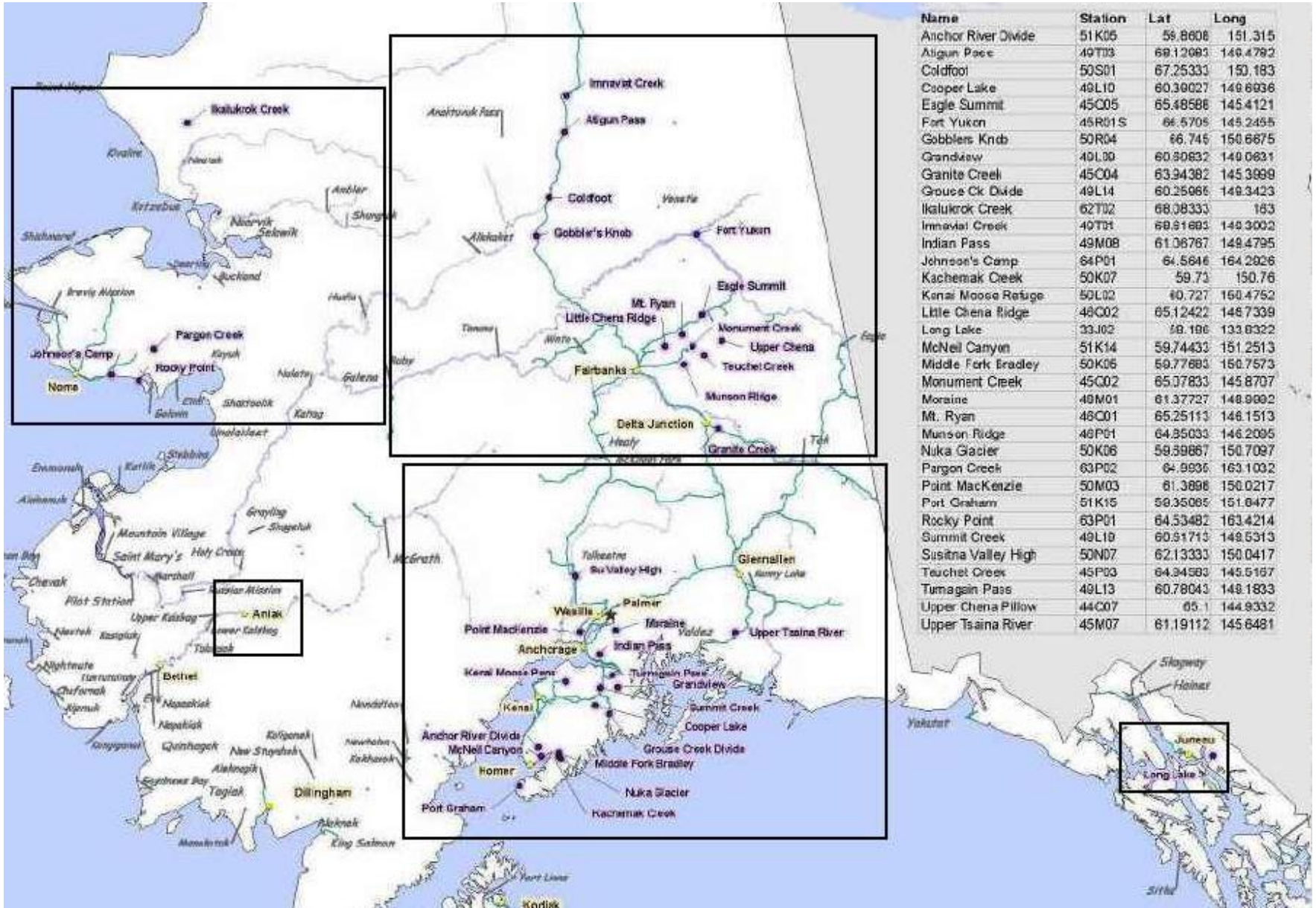
IPCC AR4, 2007

Ground-Based Observational Network and Long-term Trends

Station Network: Wx (black) and River Discharge (red)

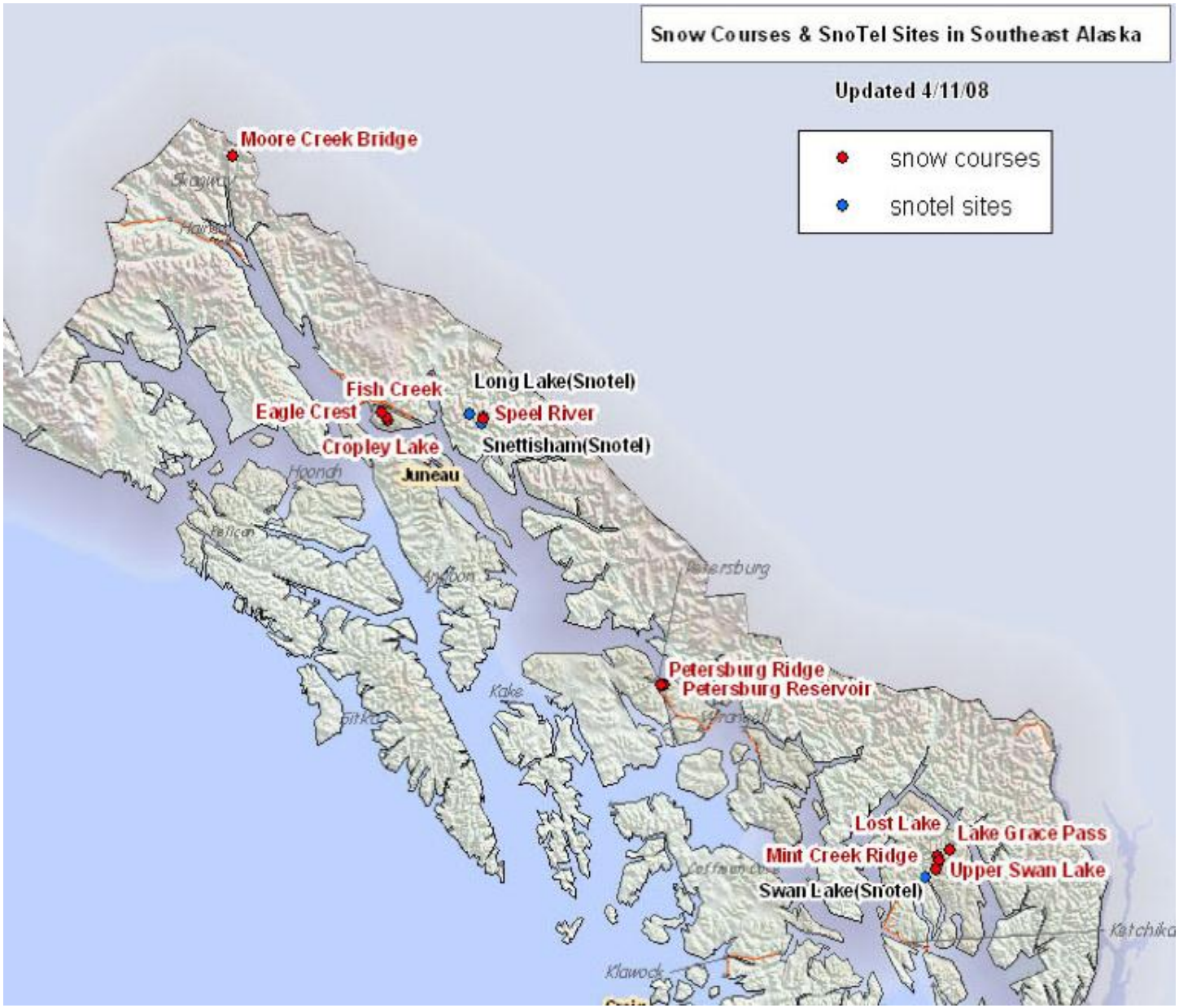


Snotel Network in AK

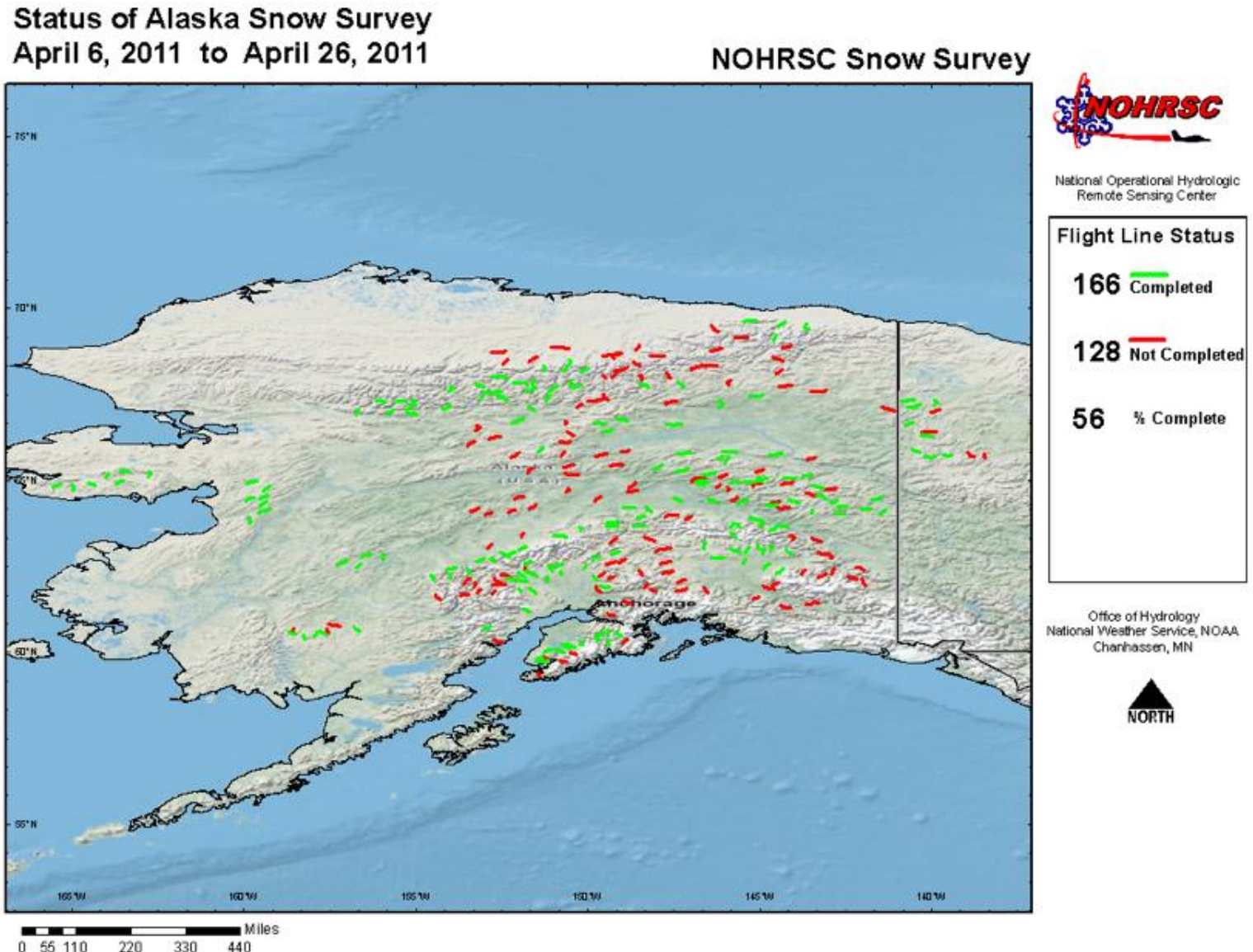


Name	Station	Lat	Long
Anchor River Divide	51K05	59.8608	151.315
Atigun Pass	49T03	68.12083	149.4792
Coldfoot	50S01	67.25333	150.183
Cooper Lake	49L10	60.39027	149.6936
Eagle Summit	45C05	65.48586	145.4121
Fort Yukon	45R01S	66.5705	145.2455
Gobblers Knob	50R04	66.745	150.6675
Grandview	49L09	60.50832	149.0631
Granite Creek	45C04	63.94382	145.3999
Grouse Ck Divide	49L14	60.25966	149.3423
Ikalukrok Creek	62T02	68.08333	163
Immaviat Creek	49T01	68.61683	149.3002
Indian Pass	49M08	61.06767	149.4795
Johnson's Camp	64P01	64.5646	164.2926
Kachemak Creek	50K07	59.73	150.76
Kenai Moose Refuge	50L02	60.727	150.4752
Little Chena Ridge	46C02	65.12422	146.7339
Long Lake	33J02	58.196	133.6322
McNeil Canyon	51K14	59.74433	151.2513
Middle Fork Bradley	50K06	59.77683	150.7573
Monument Creek	45C02	65.07833	145.8707
Moraine	49M01	61.37727	148.9992
Mt. Ryan	46C01	65.25113	146.1513
Munson Ridge	46P01	64.85033	146.2095
Nuka Glacier	50K06	59.59867	150.7097
Pargon Creek	63P02	64.9935	163.1032
Point MacKenzie	50M03	61.3898	150.0217
Port Graham	51K15	59.35065	151.8477
Rocky Point	63P01	64.53482	163.4214
Summit Creek	49L19	60.91713	149.5313
Susitna Valley High	50N07	62.13333	150.0417
Teuchet Creek	45P03	64.34583	145.5167
Tumagain Pass	49L13	60.78043	149.1833
Upper Chena Pillow	44C07	65.1	144.9332
Upper Tsaina River	45M07	61.19112	145.6481

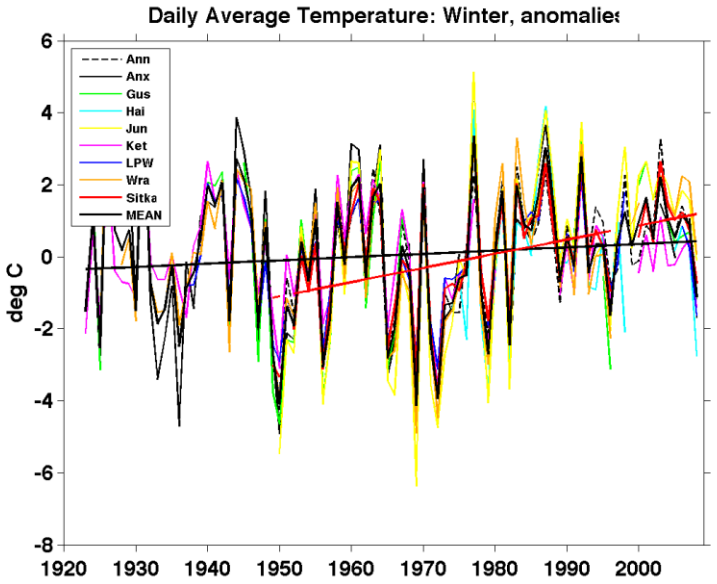
Ground-based snow surveys

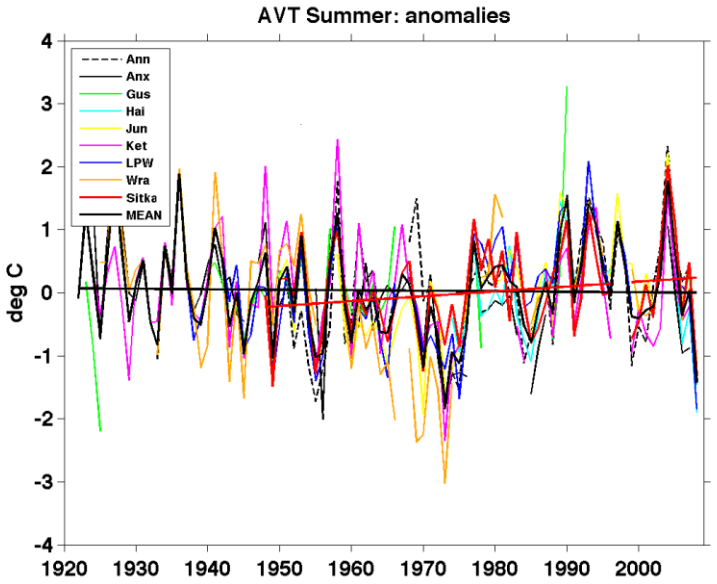


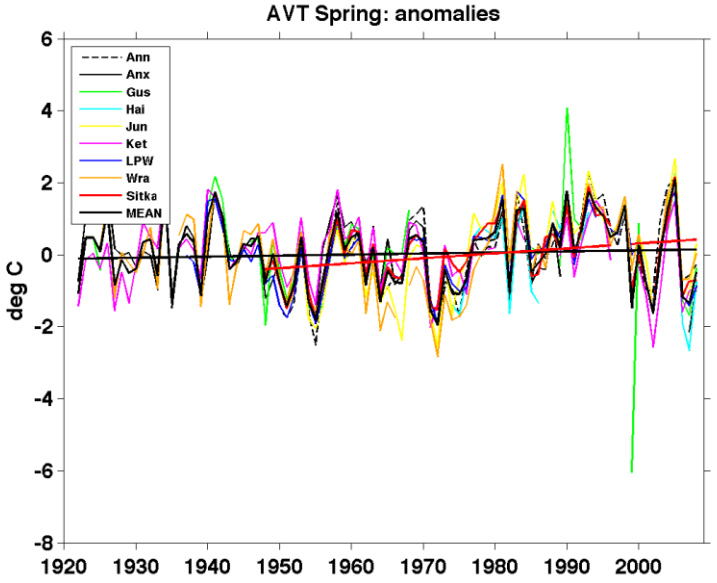
National Operational Hydrologic Remote Sensing Center

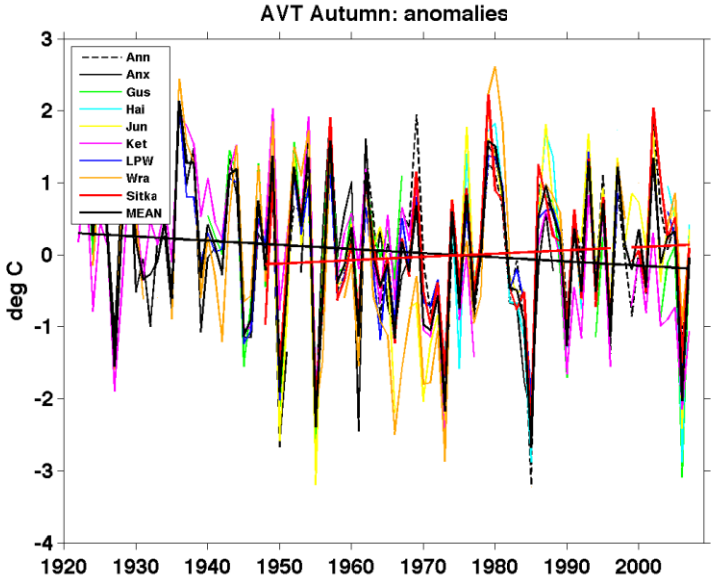


Observed Historical Average Temperature Anomalies by Season for SEAK

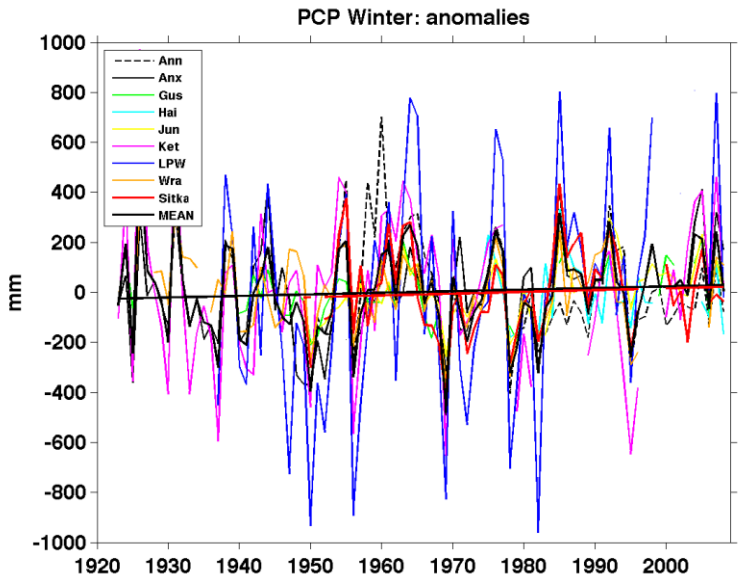


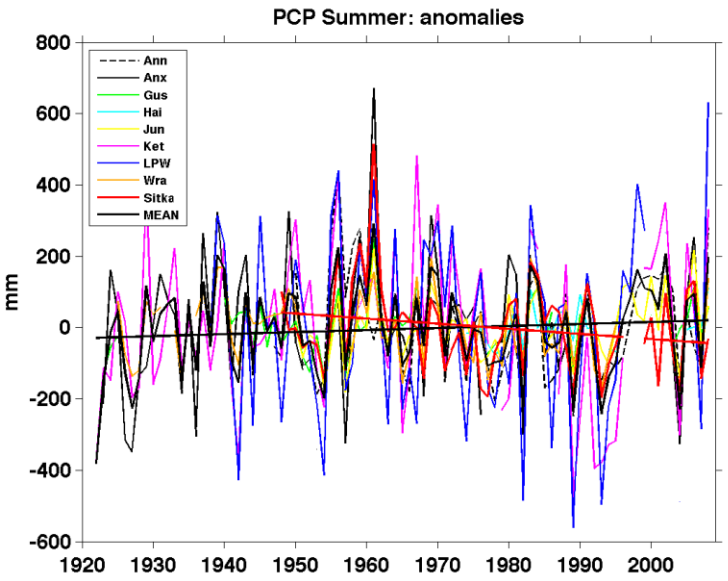


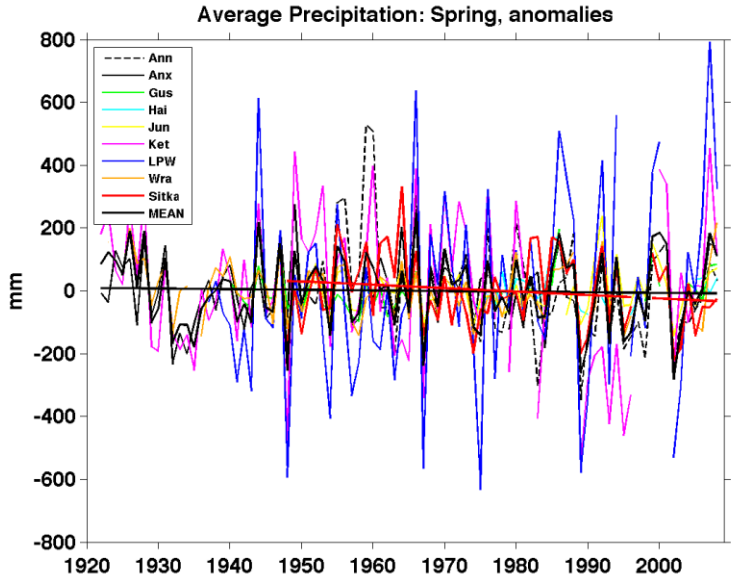


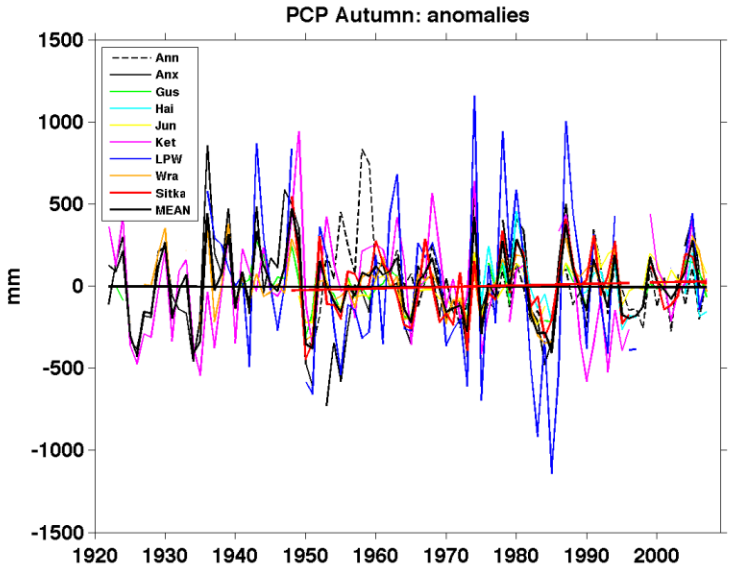


Observed Historical Precipitation Anomalies by Season for SEAK



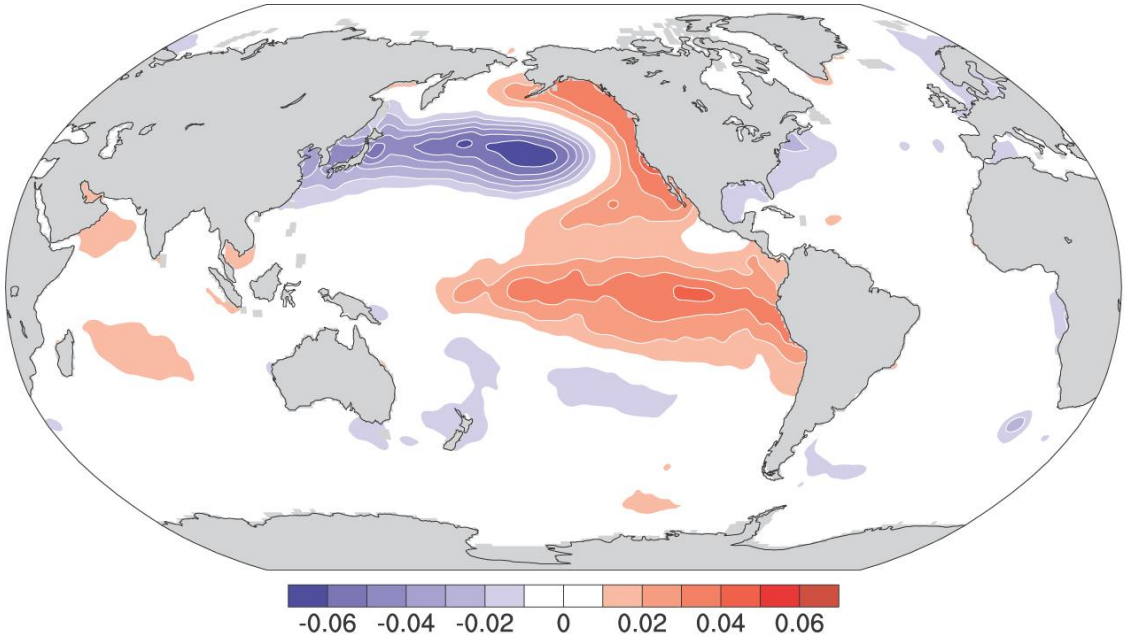


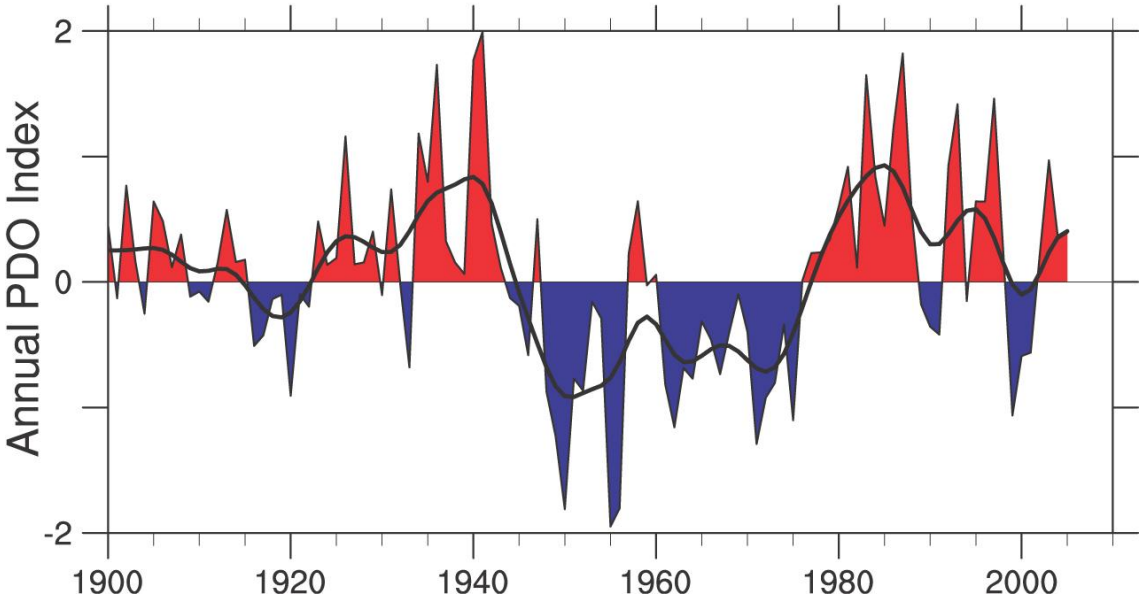




Climate Variability: working on multiple scales

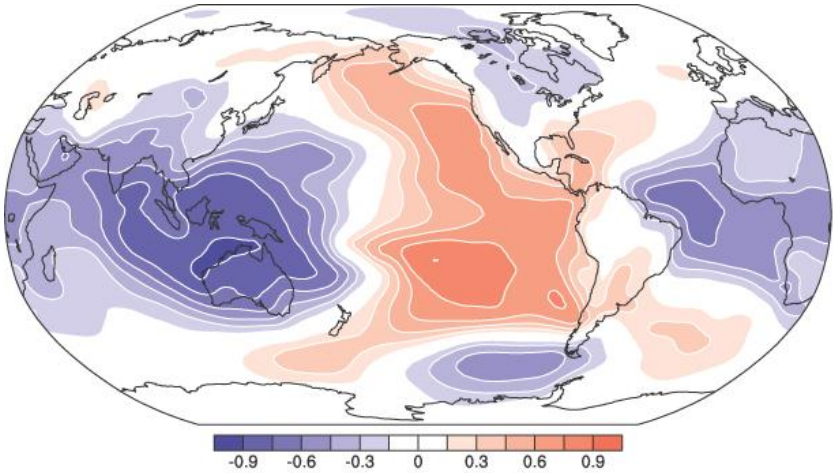
Observed Climate Variability: PDO

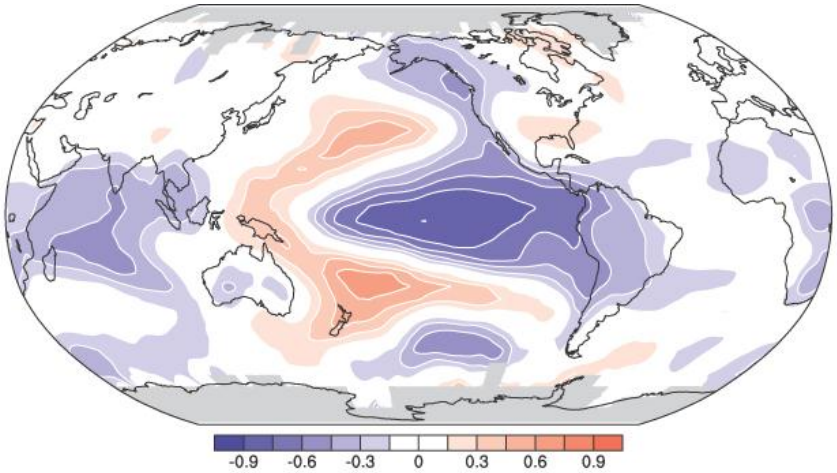


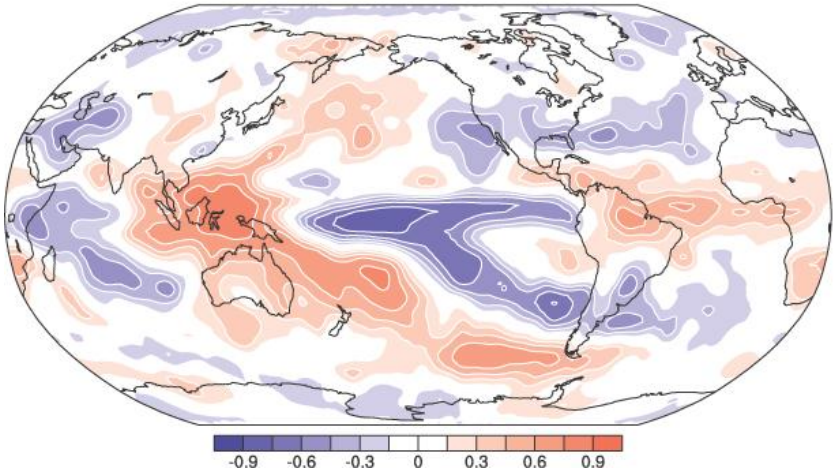


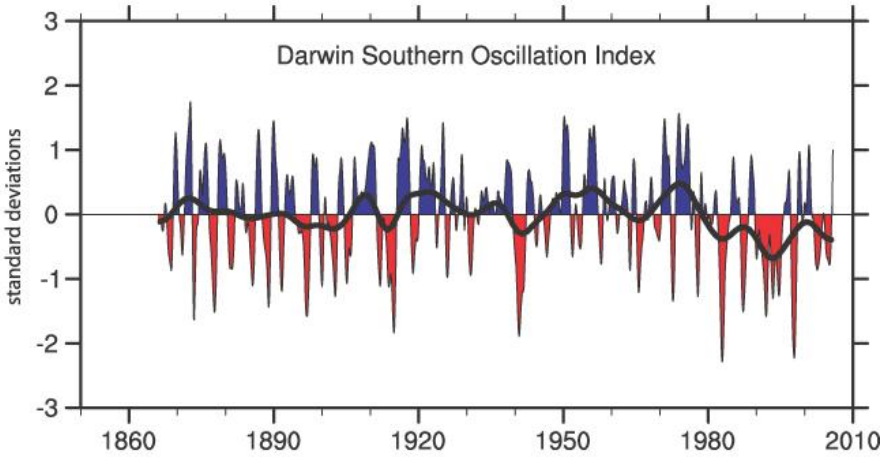
IPCC AR4, 2007

Observed Climate Variability: ENSO



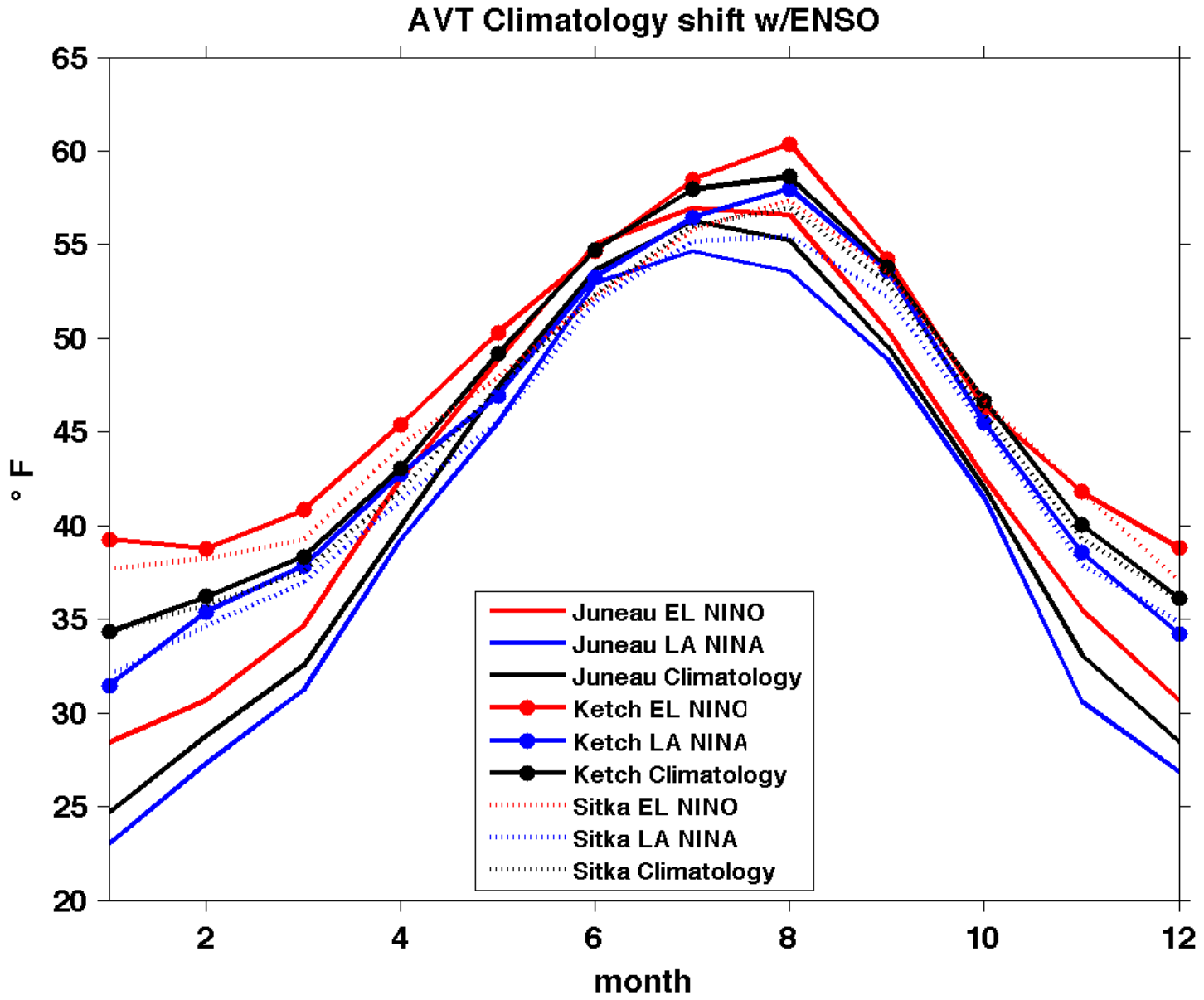




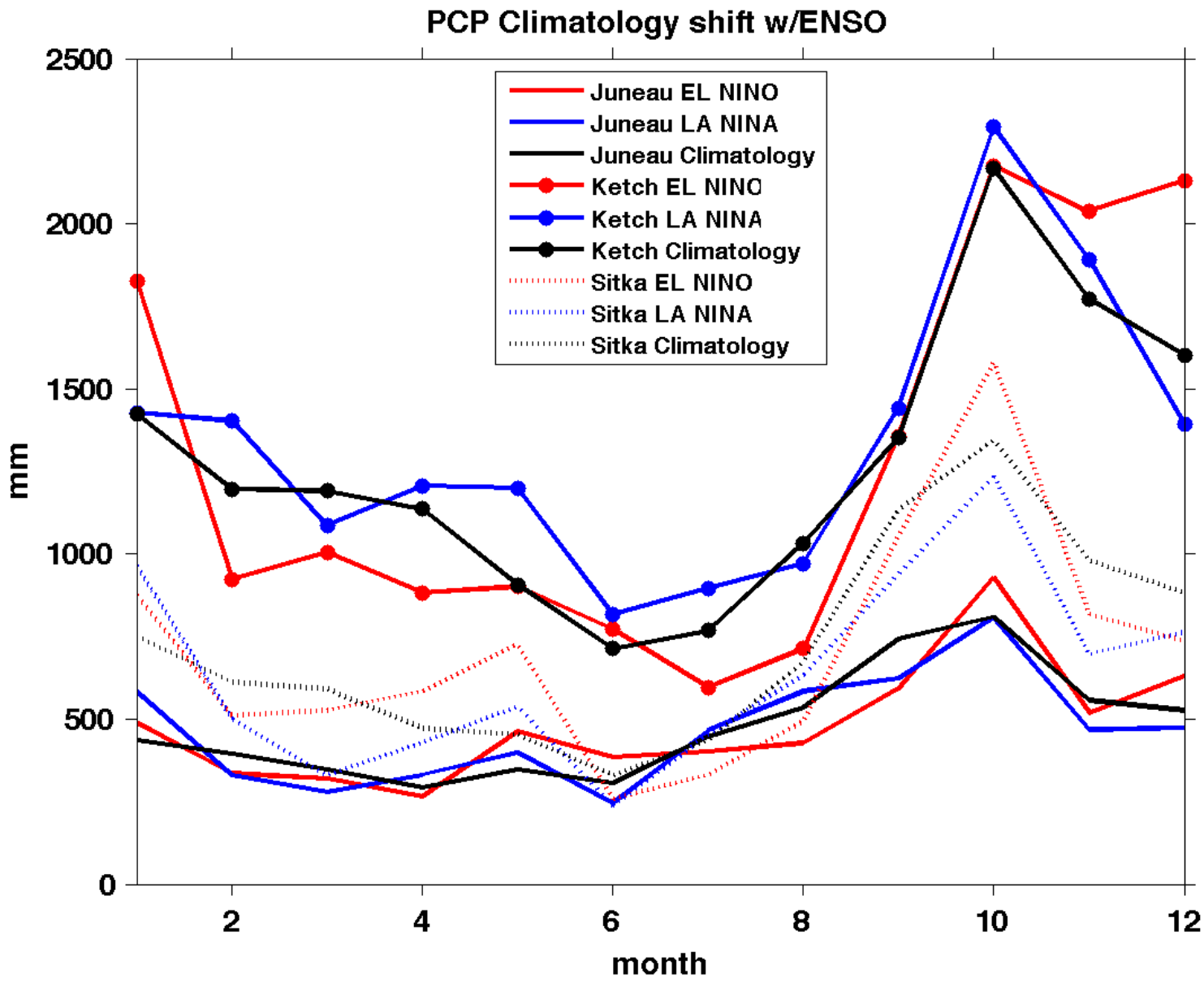


IPCC AR4, 2007

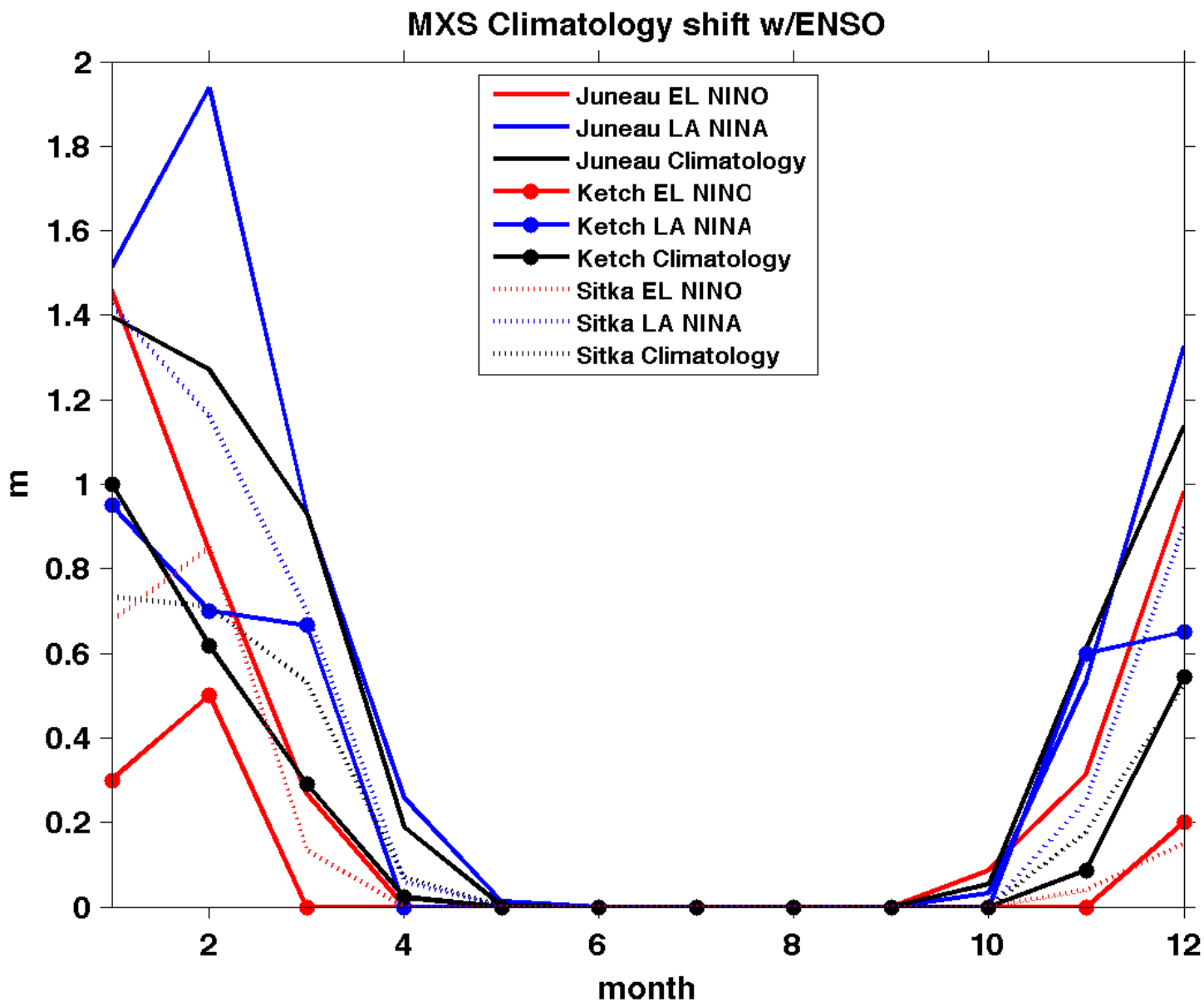
Impact of ENSO at SEAK Stations



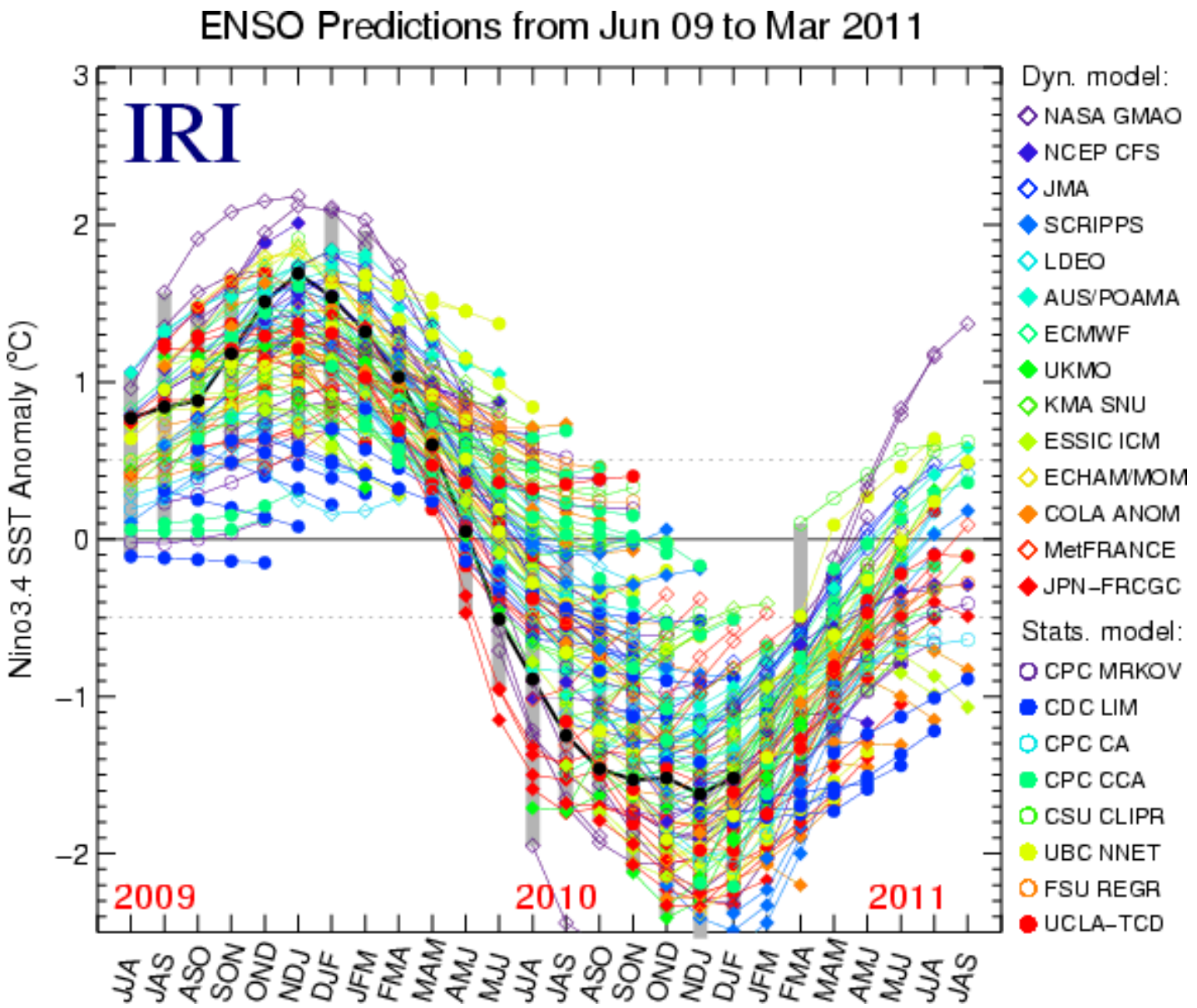
Impact of ENSO at SEAK Stations

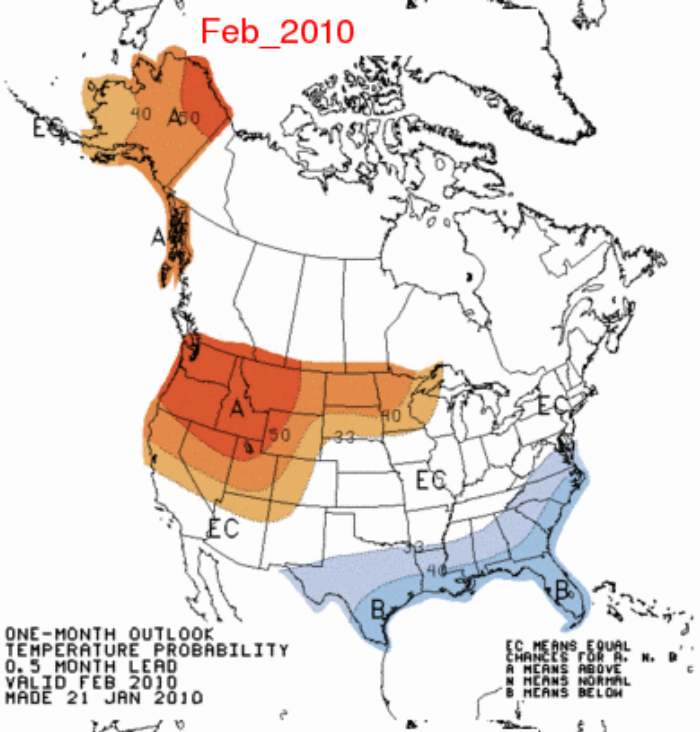


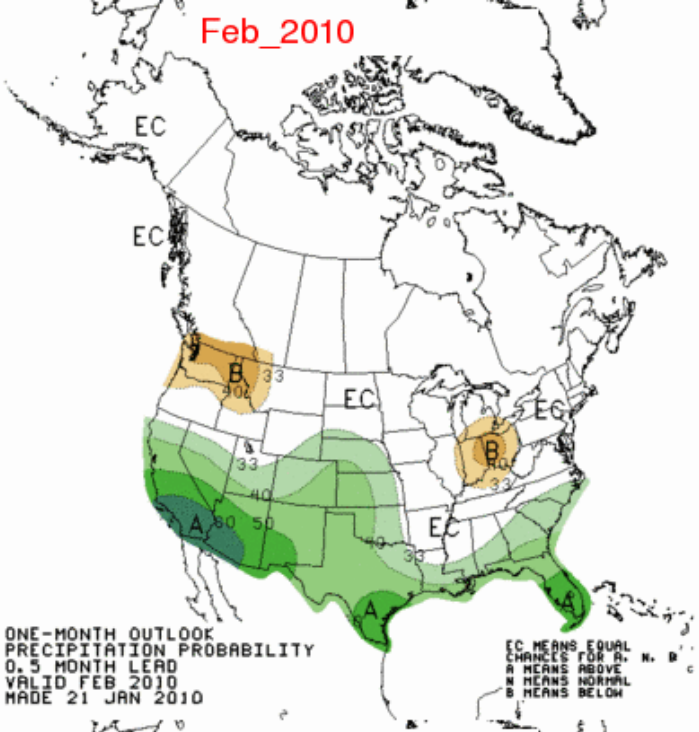
Impact of ENSO at SEAK Stations



Predictability of ENSO




Feb_2010
ONE-MONTH OUTLOOK
TEMPERATURE PROBABILITY
0.5 MONTH LEAD
VALID FEB 2010
MADE 21 JAN 2010
EC MEANS EQUAL CHANCES FOR A, N, B
A MEANS ABOVE
N MEANS NORMAL
B MEANS BELOW


Feb_2010
ONE-MONTH OUTLOOK
PRECIPITATION PROBABILITY
0.5 MONTH LEAD
VALID FEB 2010
MADE 21 JAN 2010
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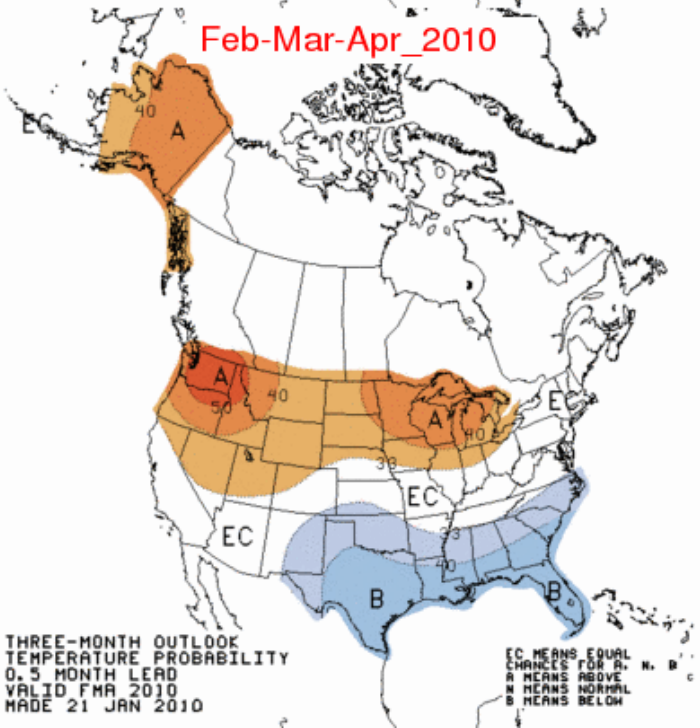
Feb-Mar-Apr_2010
THREE-MONTH OUTLOOK
TEMPERATURE PROBABILITY
0.5 MONTH LEAD
VALID FMA 2010
MADE 21 JAN 2010
EC MEANS EQUAL CHANCES FOR A, N, B
A MEANS ABOVE
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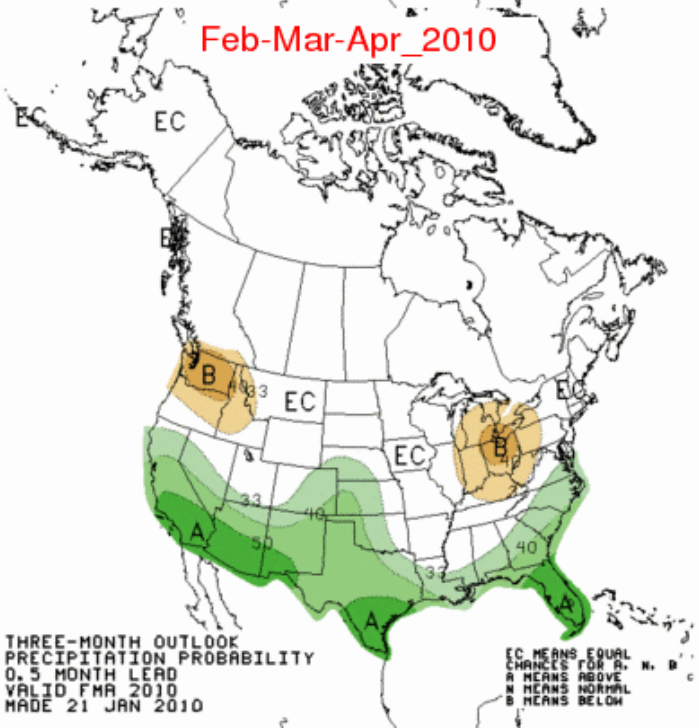
B MEANS BELOW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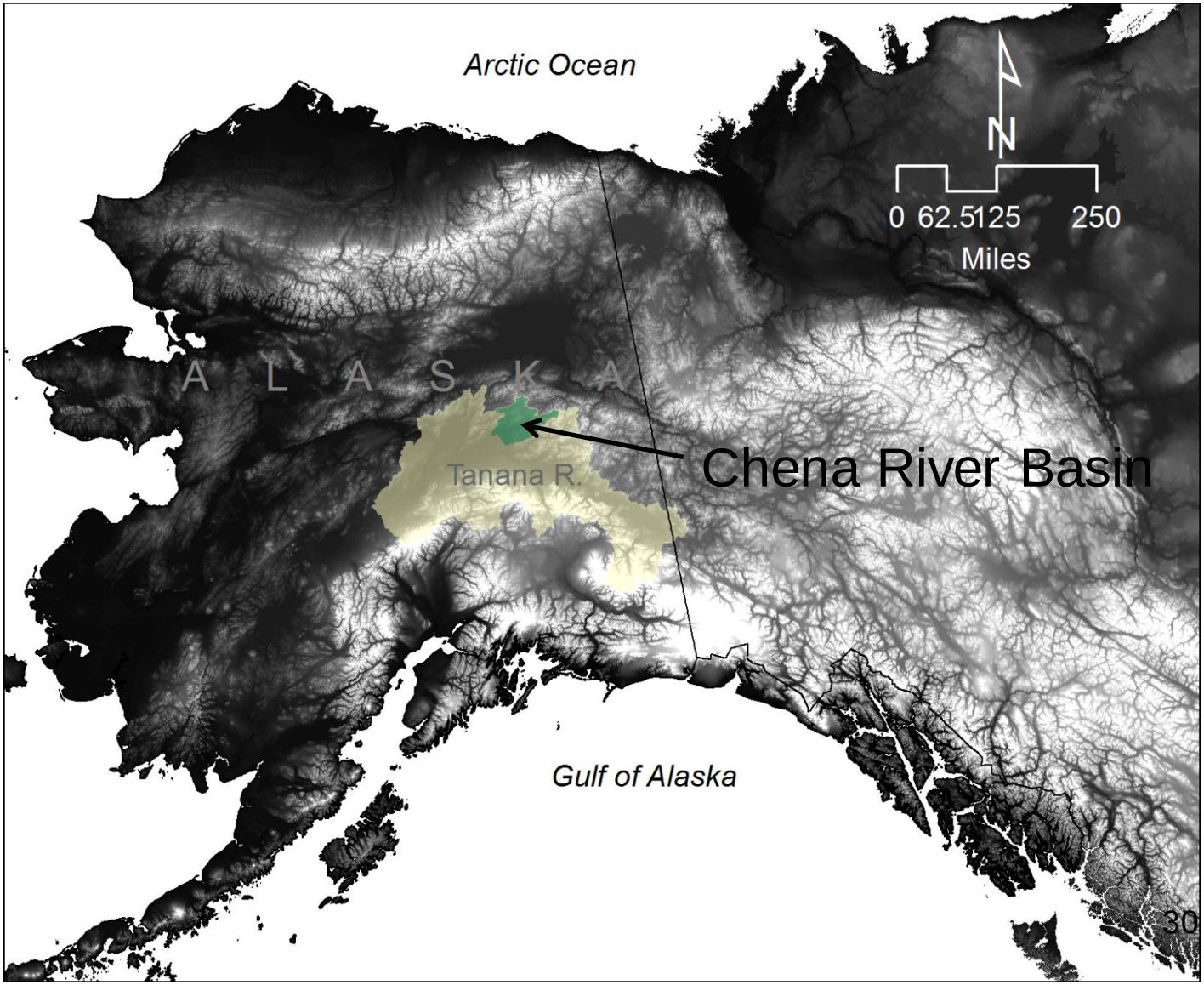
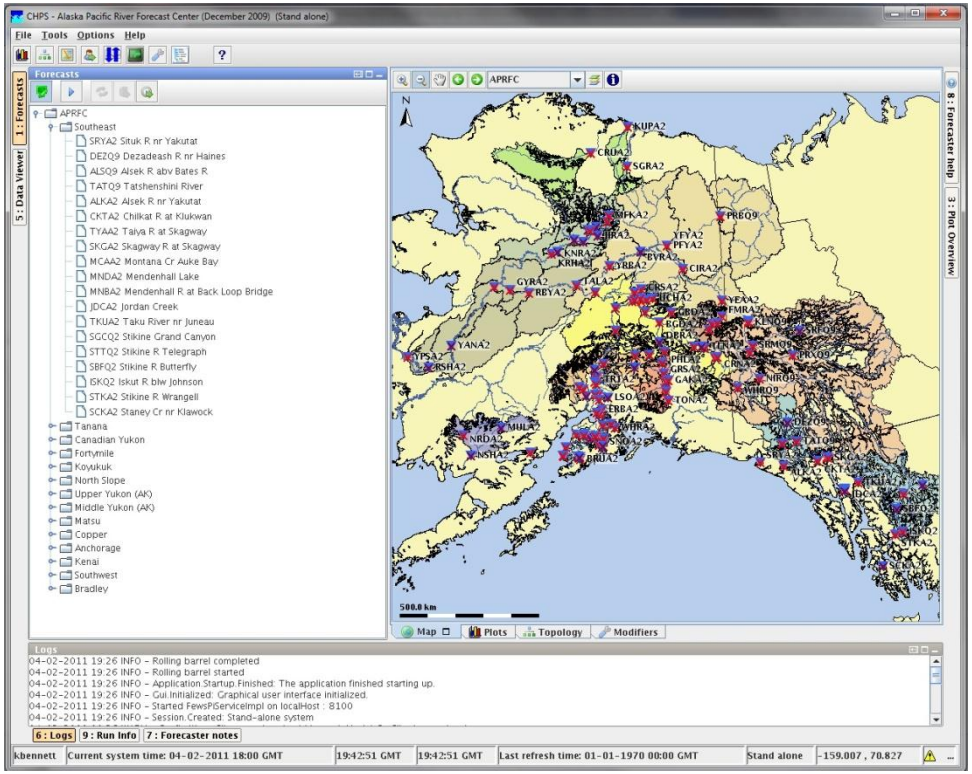
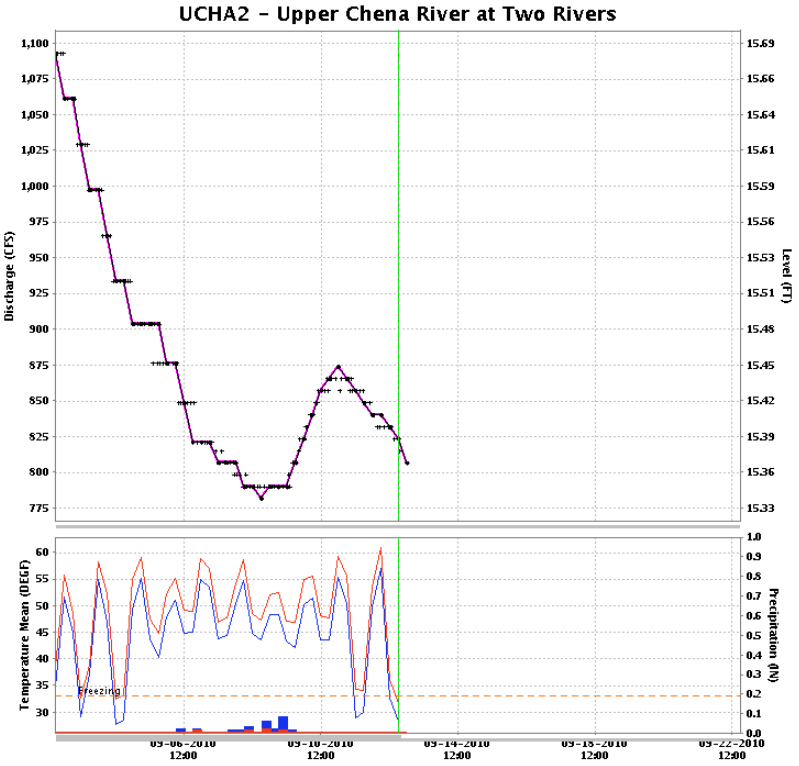
High Latitude Proving Ground Snow Products: collaboration with AK River Forecast Center

Study Site: Chena River Basin



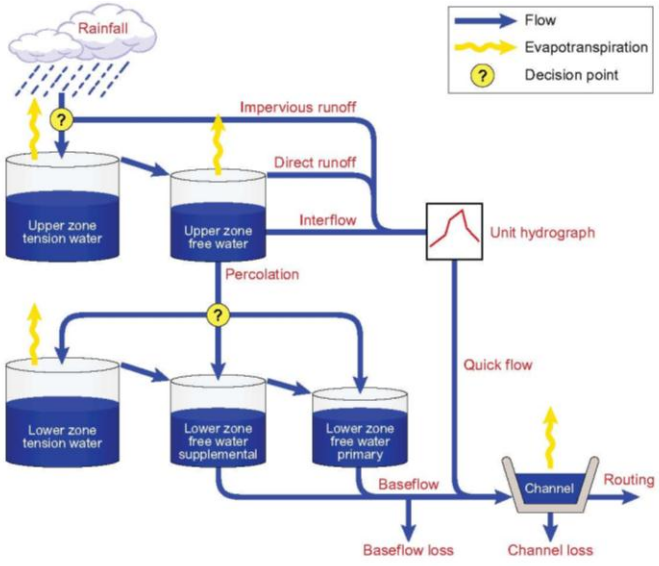
NWS River Forecast Center Flood Early Warning System: CHPS





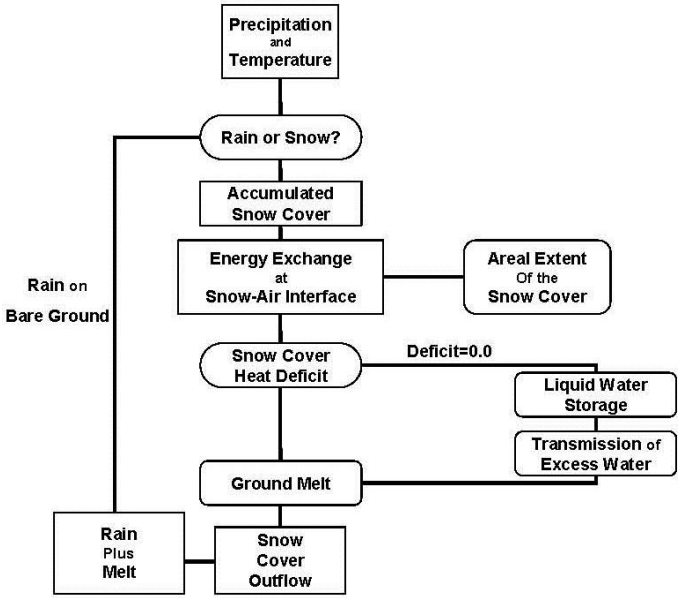
SAC-SMA Hydrologic Model

- **SAC**ramento **S**oil **M**oisture **A**ccounting model – conceptual water balance model (Burnash et al. 1973)
- Frozen ground iteration, December 2010



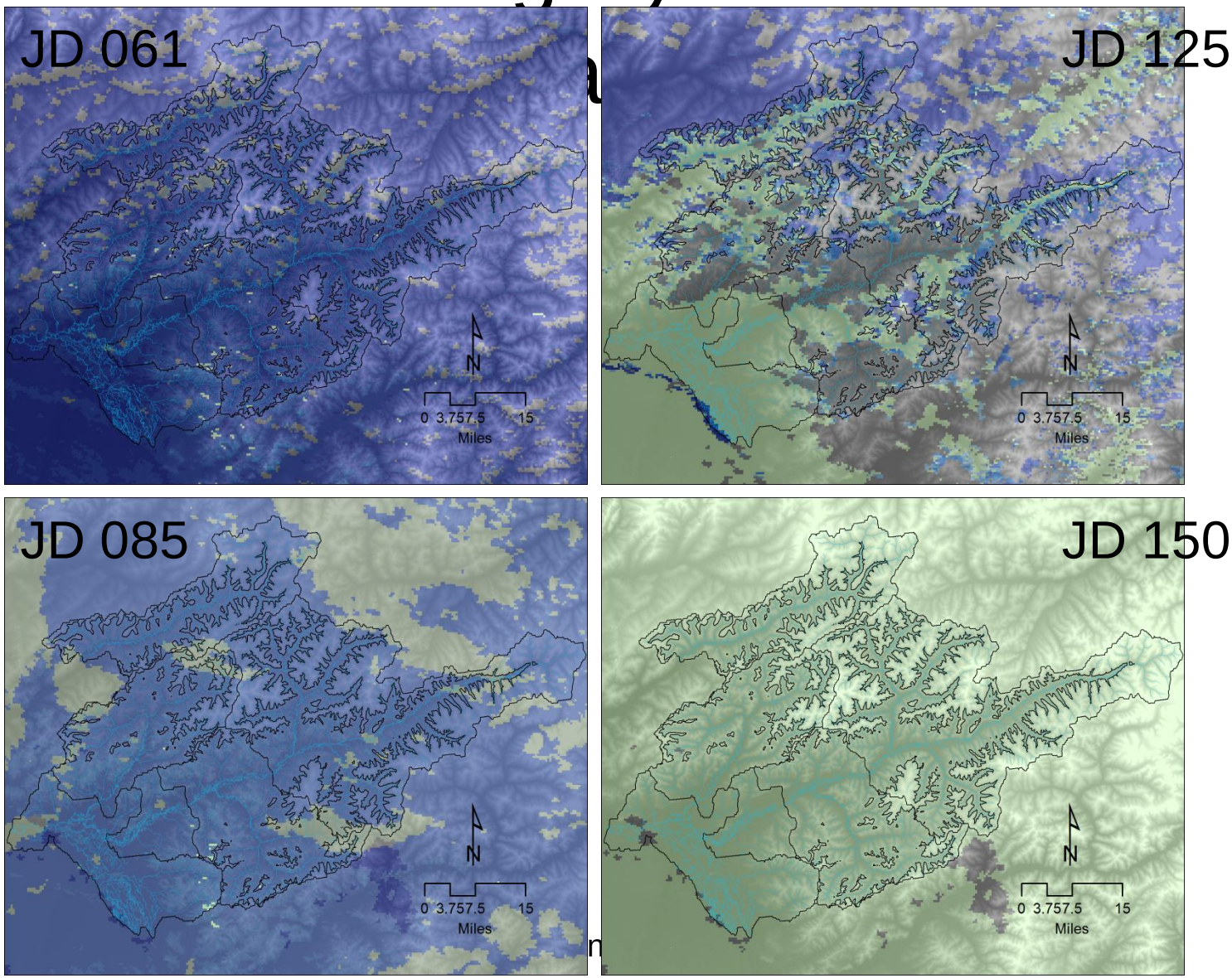
SNOW-17

- Air temperature index model
- Inputs are T & P
- Watersheds divided into two or three elevation zones to estimate the melt from the snow cover to a runoff/rainfall model (SAC-SMC)
- Main processes simulated by SNOW-17 are:
  - form of precipitation (snow or rain)
  - accumulation of snow cover
  - energy exchange at the snow-air interface
  - internal states of snow cover (temperature liquid/frozen water content, density, etc.)
  - transmission of liquid water through the snowpack, and
  - heat transfer at the soil-air interface.



Excerpted from Anderson, 2006

MODIS Imagery: Snow Cover

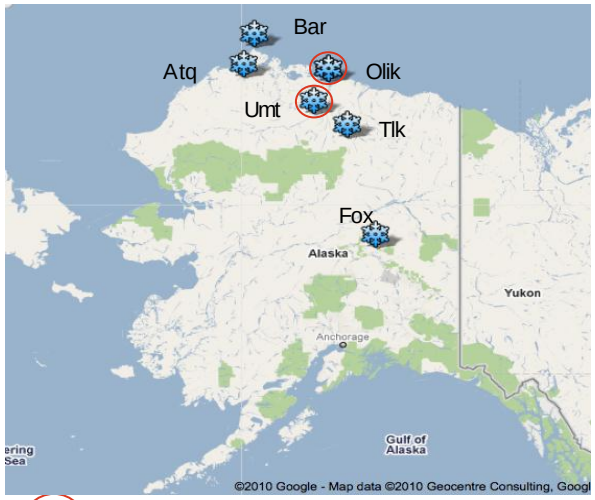


Methods

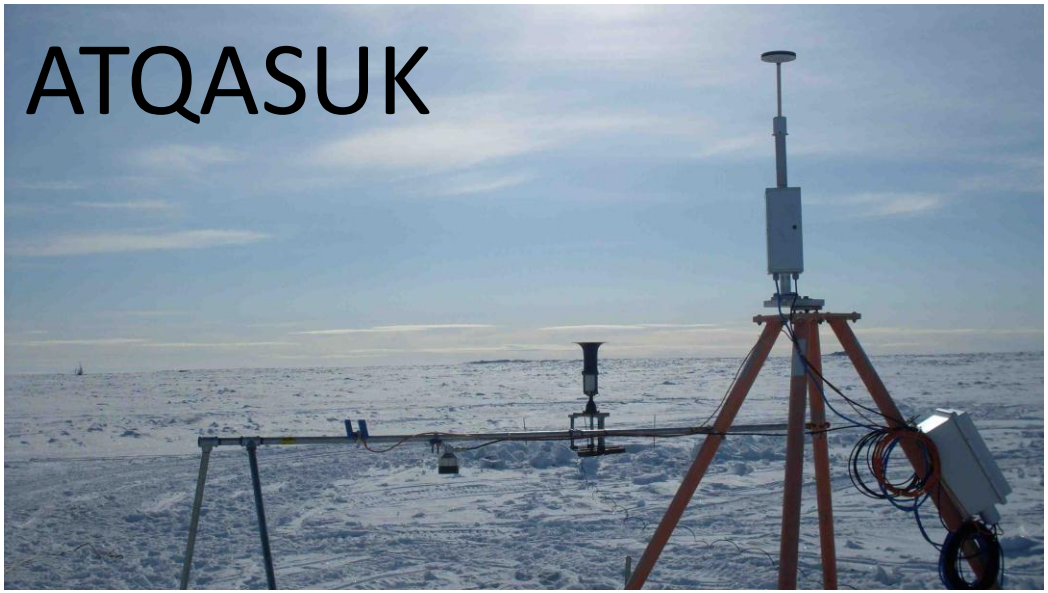
- Analysis of MODIS data (2000 to 2011), relationships to t & p, watershed characteristics (aspect)
- Calculate for each sub-watershed snow cover fractional extent (2000 to 2011) through snow melt season
- Update snow cover fractional extent in models
- Analysis of extreme events
  - Examine the watershed response and characterize these events (climate, antecedent moisture conditions, snowmelt dynamics, active layer soil moisture in summer)
  - Historic and future analyses of events to understand how these events may have changed through time, or might be predicted to change into the future.

Other tools in our Toolbox

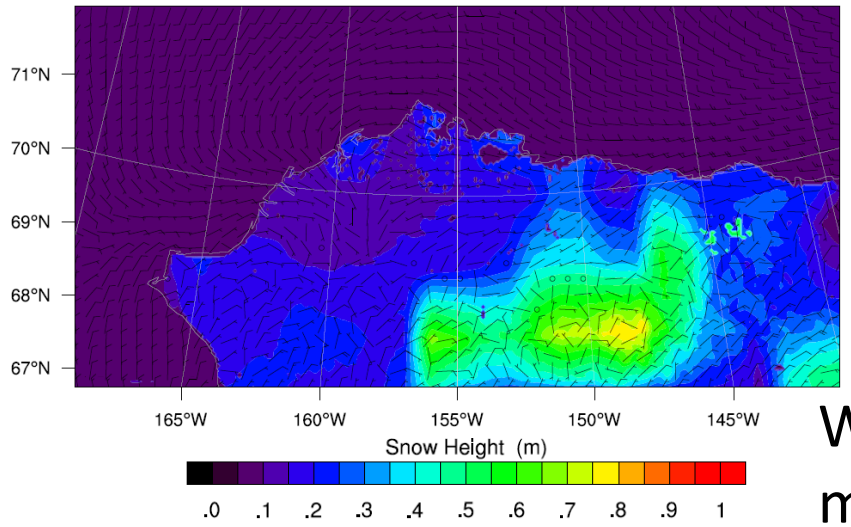
Arctic Transportation Networks: improved monitoring and prediction of blowing snow



= deploying in summer 2011



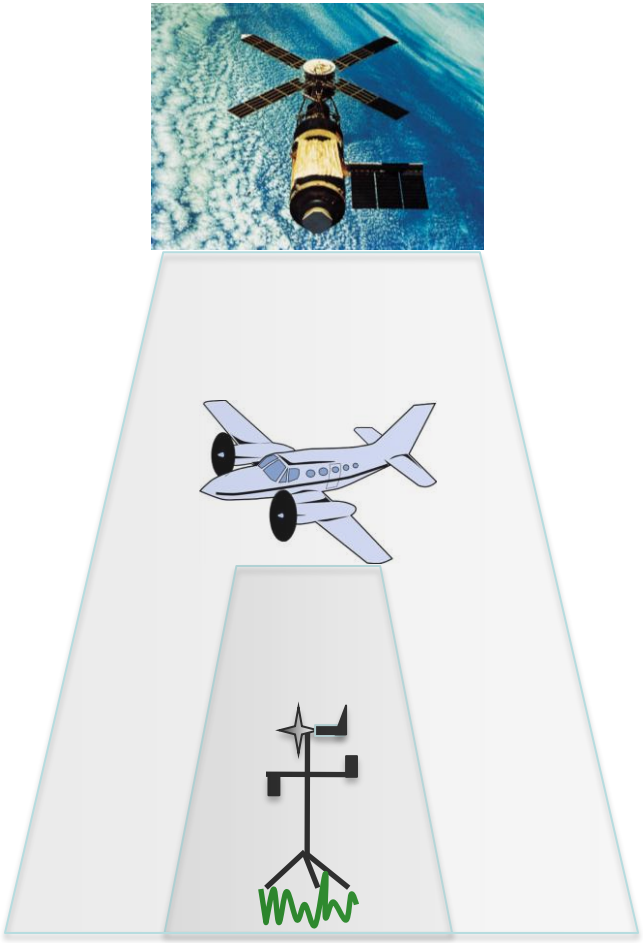
Used for in situ studies and validation of models



WRF model

J. Cherry

Our Observing Approach: multiple scales of land-atmosphere interactions (energy, water, ecosystems, etc)



Satellite

Airborne

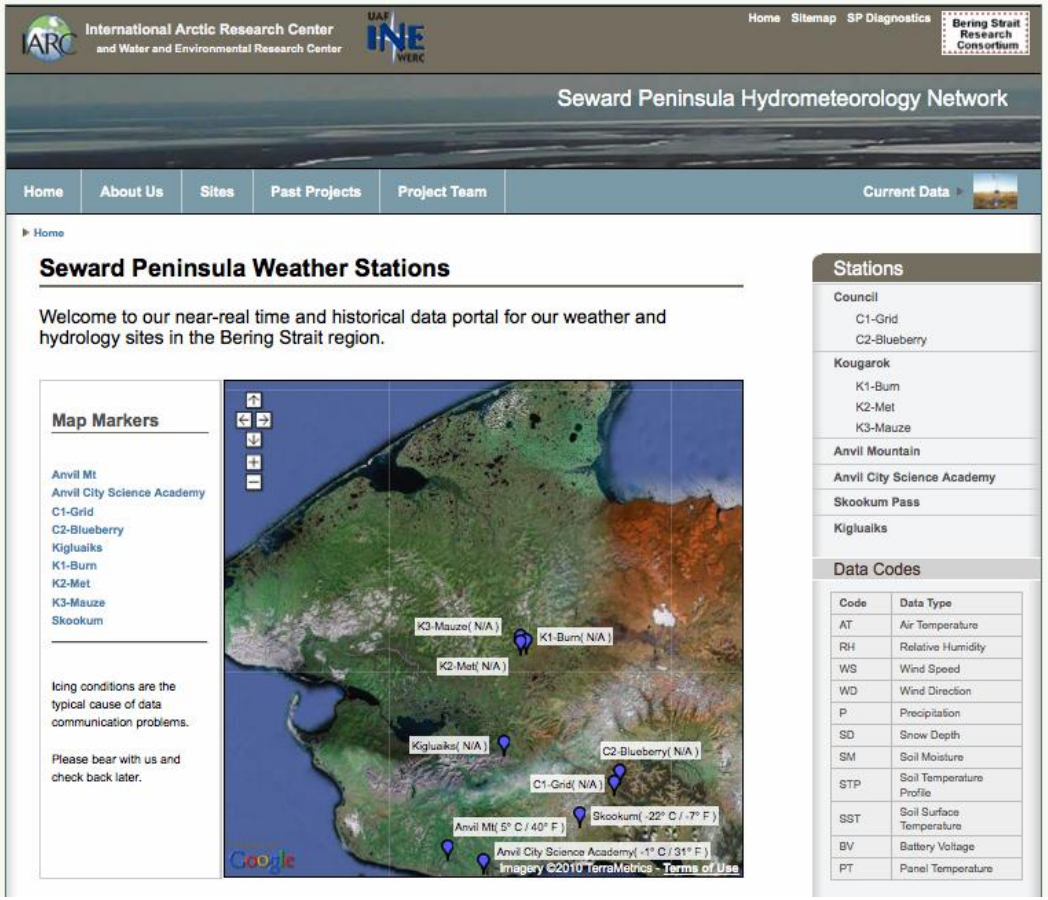
In situ

Example: Seward Peninsula

http://ine.uaf.edu/werc/projects/seward/

Photo: R. Busey

Photo: J. Cherry



Real Time Data pulled over a network of radios and repeaters

Uploaded to Internet at Nome; web services

Archived at UAF

Partnerships: Northwest Campus of UAF in Nome, Anvil City Science Academy (Jr. High), Kawerak Native Corp, National Park Service

Building Airborne Remote Sensing

RFC Runs a Pilot Observer Program in Alaska

Airborne imaging: optical, IR, hyperspectral, multispectral, SAR (x-band)

Dangerous Ice Project

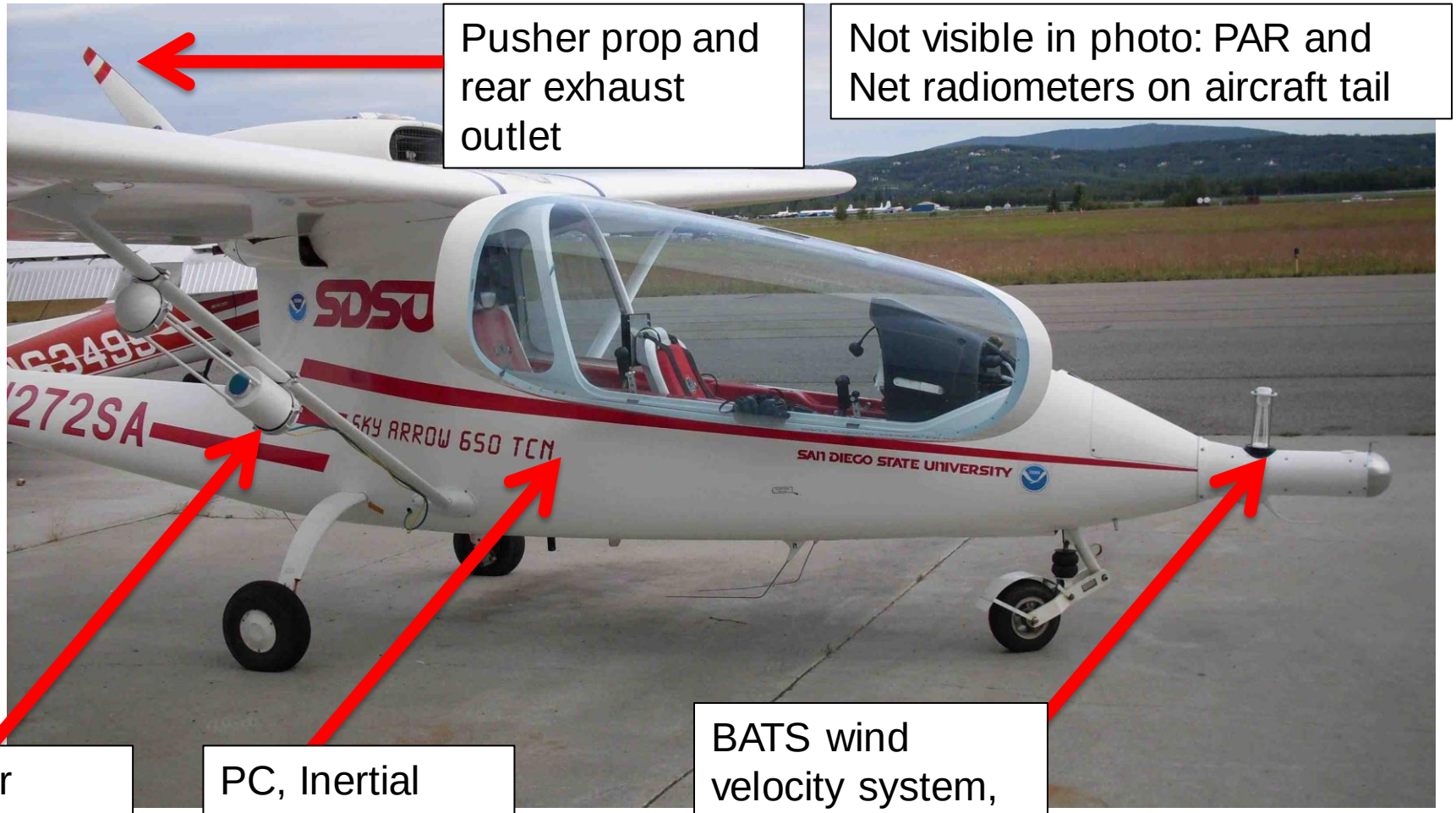
Atmospheric Water Isotope Cal/Val for Spaceborne TES sensor: partnership with JPL

- Creation of water isotope atlas for the state by flying a water vapor analyzer on an aircraft
- Science questions are the source regions for precipitation, water budgets of surface waters, and the role of different types of vegetation in fractionating isotopes
- Stable isotopes have now been put into some of the climate models
- Existing map of water isotopes for surface water bodies in AK
- Never before sampled from aircraft

Picarro L1115-I Isotopic Liquid Water and Water Vapor Analyzer

Photo: Picarro

SDSU Carbon/Methane Low Altitude Sampling Aircraft used in NASA CARVE Program



Pusher prop and rear exhaust outlet

Not visible in photo: PAR and Net radiometers on aircraft tail

Licor methane sensor

PC, Inertial Nav System, GPS Clock, etc

BATS wind velocity system, Temp, RH, and CO2

Photo: J. Cherry, 2011

Discussion Points

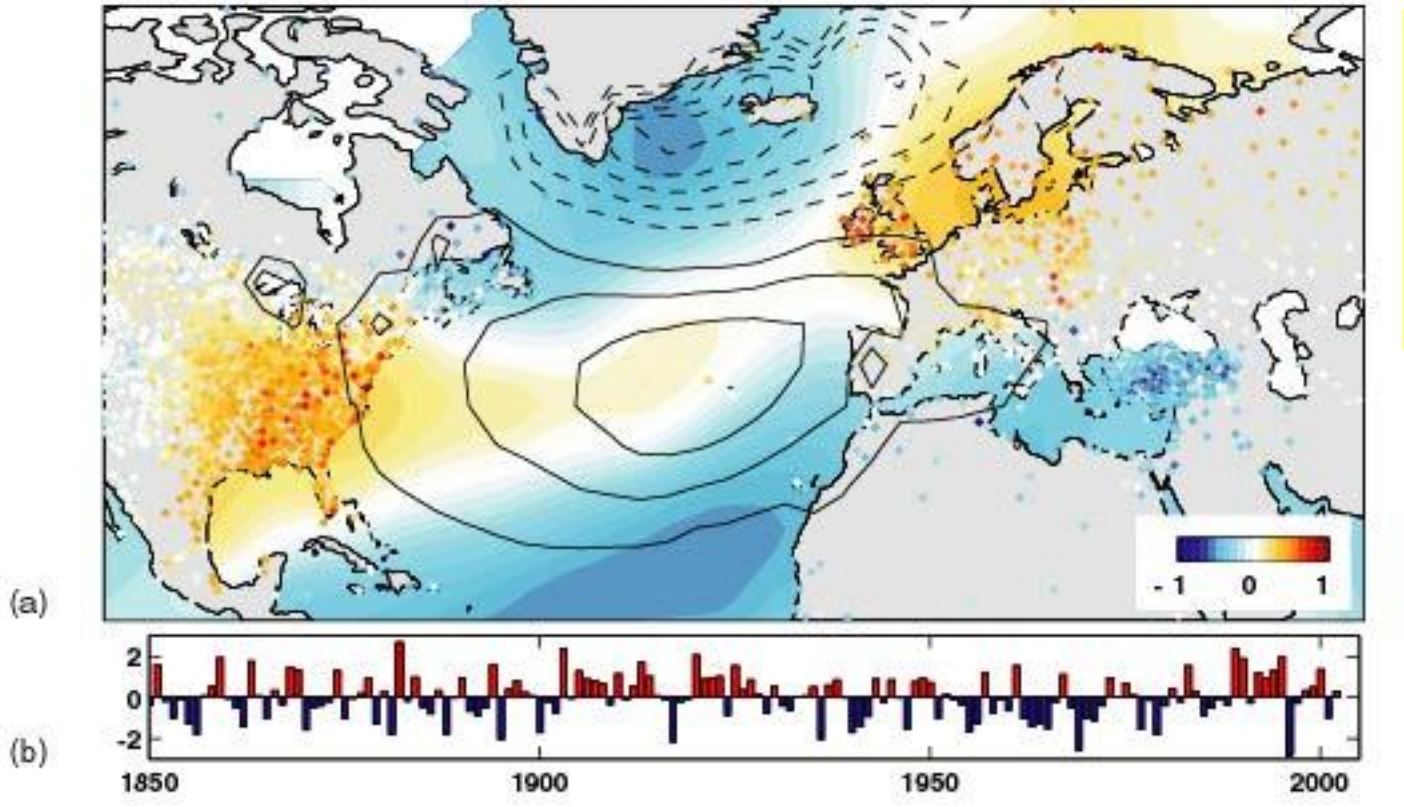
- Moving from snow covered area to fractional snow covered satellite products? (MODSCAG, Painter et al.)
- Develop sophisticated data assimilation system or make use of an existing one (LIS) ?
- Improved airborne techniques for estimating snow cover/SWE in mountainous areas?
- Improved support for an *in situ* high elevation station network?
- Changing role of glacier contributions to runoff?
- Role of improved seasonal climate prediction?
- Development of improved runoff forecasting?
- Issues for new development in SEAK and railbelt are quite similar

Questions?

Contact: jcherry@iarc.uaf.edu

Physical Impacts of the NAO

data



NAO Index is the highly correlated with climate fields

NAO Index (Jones 1997) and :

correlation with DJFM SST (Kaplan et al 1998)

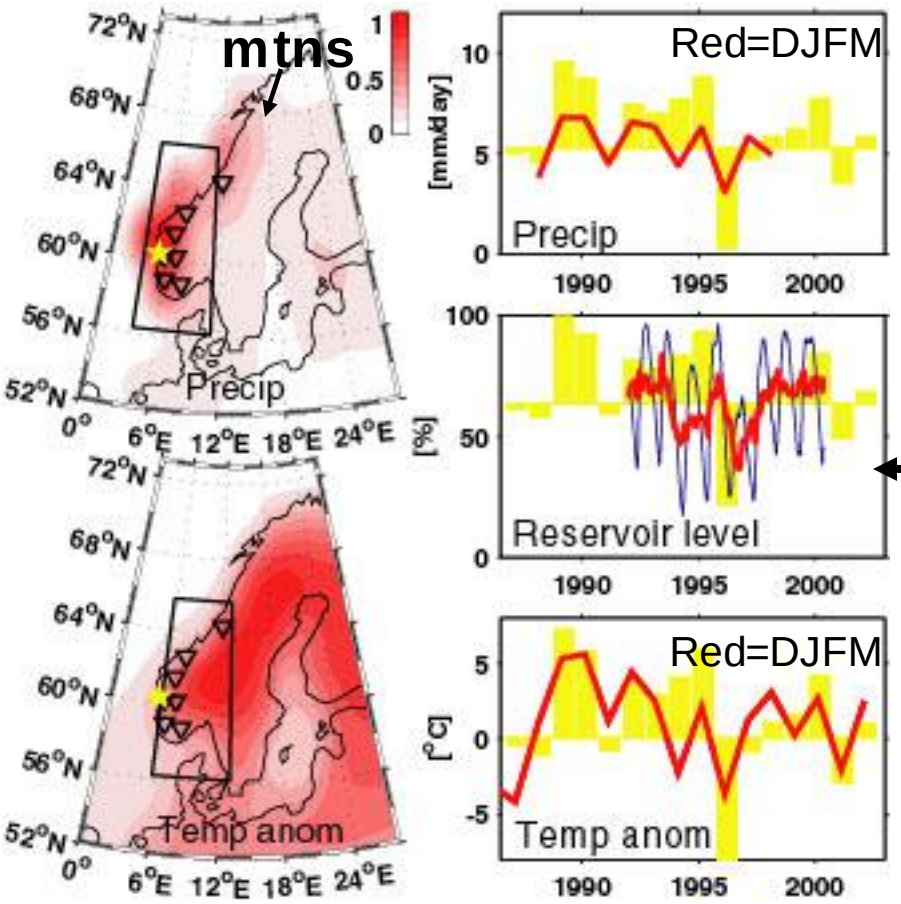
correlation with DJFM SAT (NCDC/GHCN)

covariance with DJFM SLP at 0.3 HPa contour intervals (NCEP reanalysis)

Trends:
upward?
persistent?

Story Preview: Impacts of the NAO on Scandinavia's Climate and Energy Sector

First mode of variability in precip and temp look like the NAO in time and space



PCs

EOFs

Reservoir levels show similar patterns of variability (stations, not PC)

(Red=annual mean+weekly level-seasonal cycle)

★ = Bergen, **will use this from now on**

▽ = Major reservoirs

Data: Xie & Arkin, NCEP, Statistics Norway

Sedimentation's impact on Hydropower

Sedimentation can reduce the size of the reservoir and causes abrasion of turbines and other infrastructure

Erosion and climate are strongly coupled

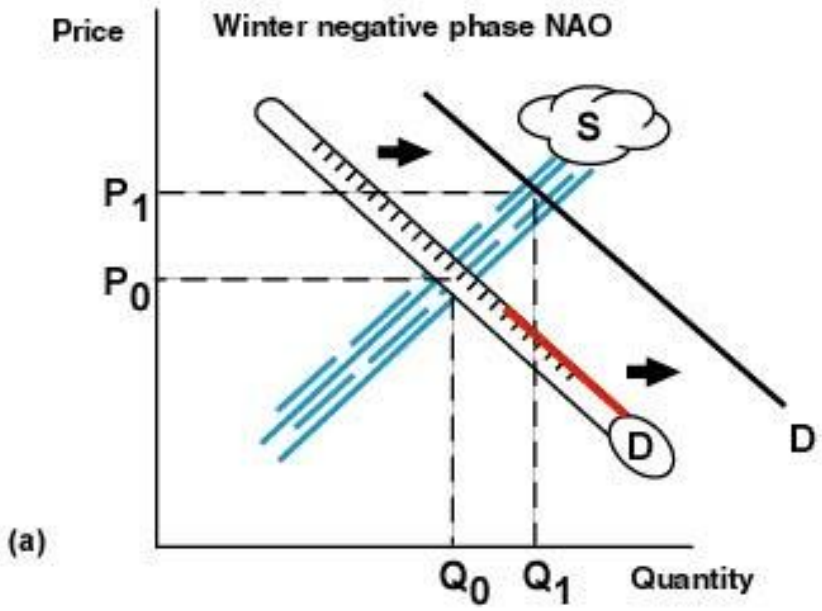
Erosion may be accelerated by melting of glaciers in the watershed

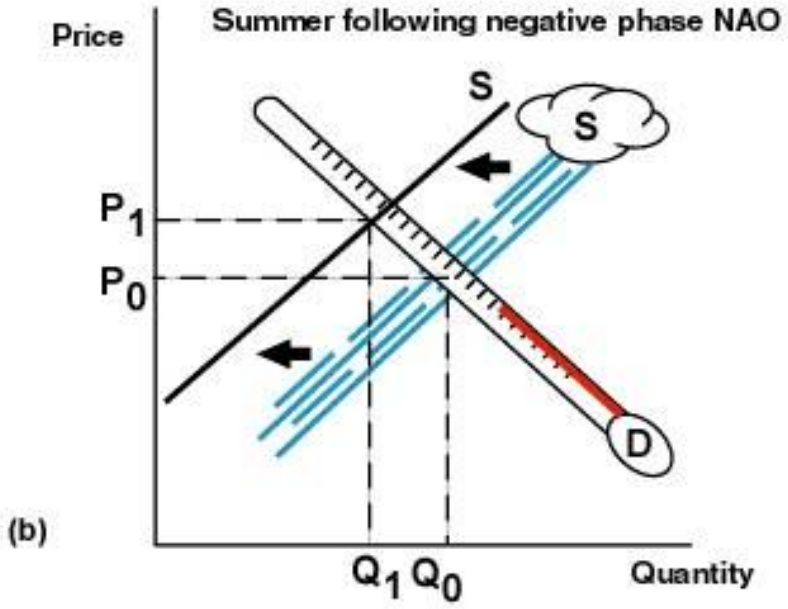
Market Setting

The 1996-1997 event

A conceptual model, illustrated by the 1996-1997 NAOI negative event, provides a hypothesis for the physical mechanisms behind an NAO impact on the energy sector

S=amt producers willing to sell for each price on the market, D=same, but for consumers buying





Norskhydro streamflow

r =+0.7

Reservoir level

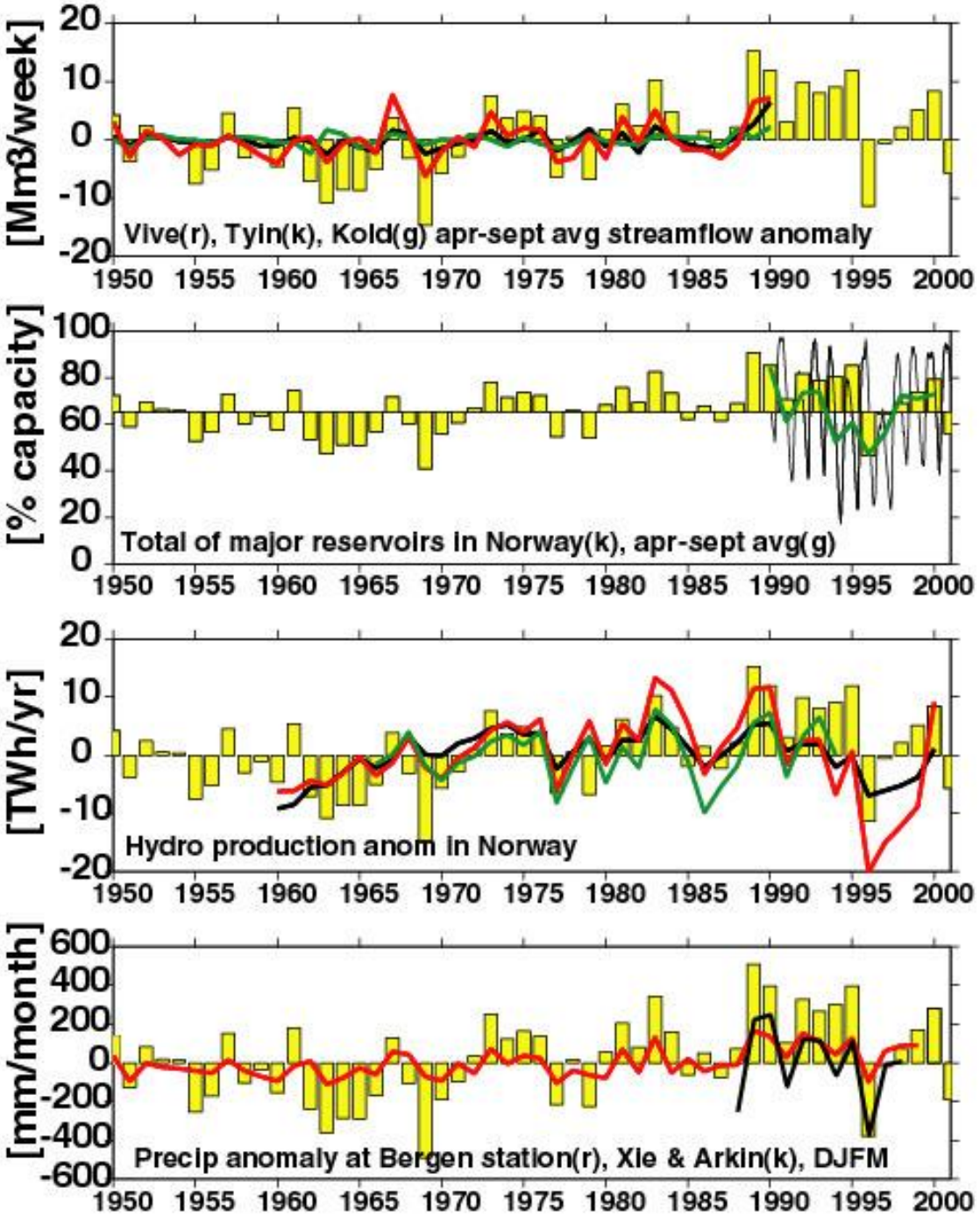
r =+0.6

Hydropower production anomaly

r ~+0.5

Precipitation anomaly (1994-5 off)

r =+0.8



SUPPLY SIDE

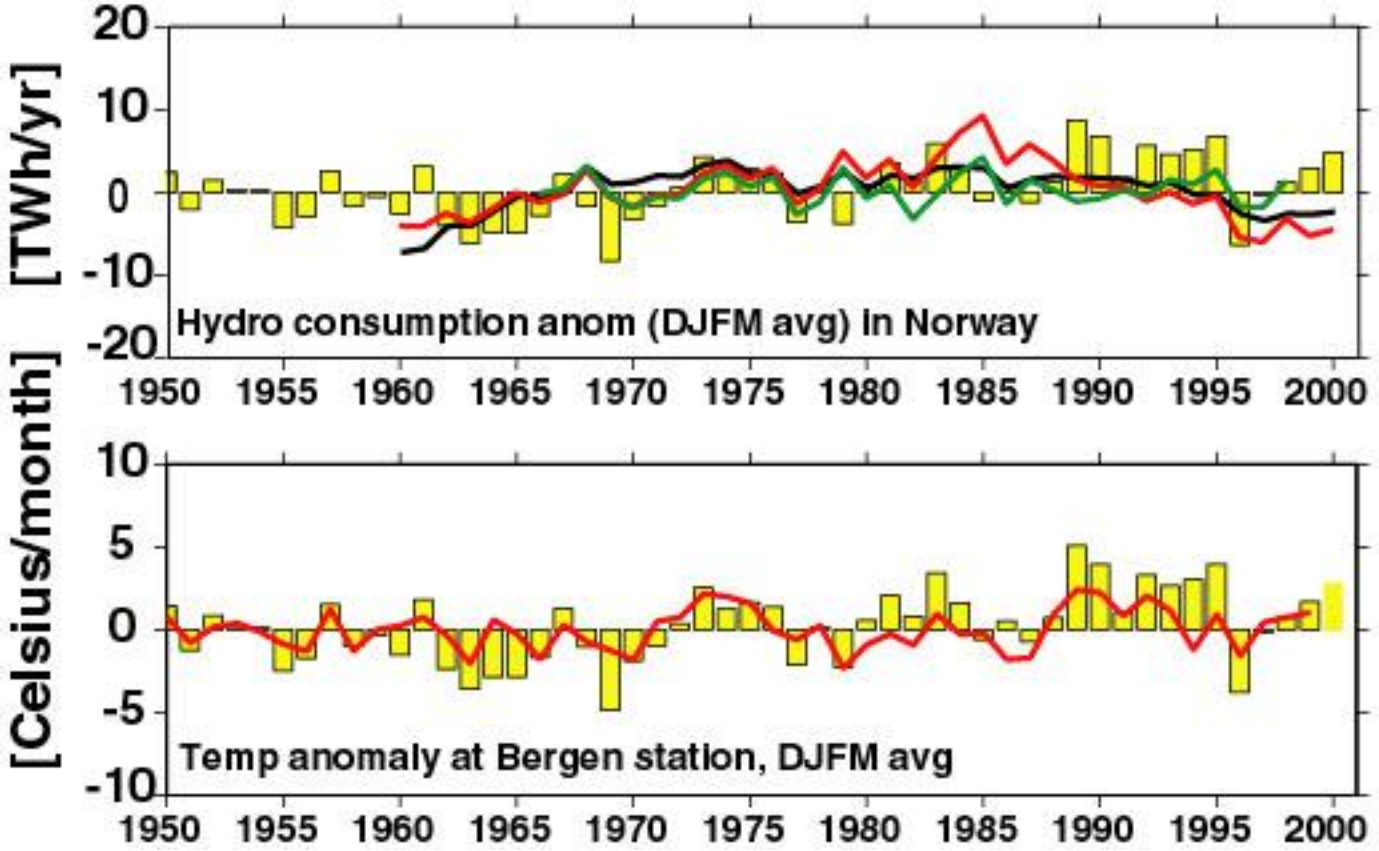
Hydropower consumption anomaly

r ~ - 0.5

Temperature anomaly

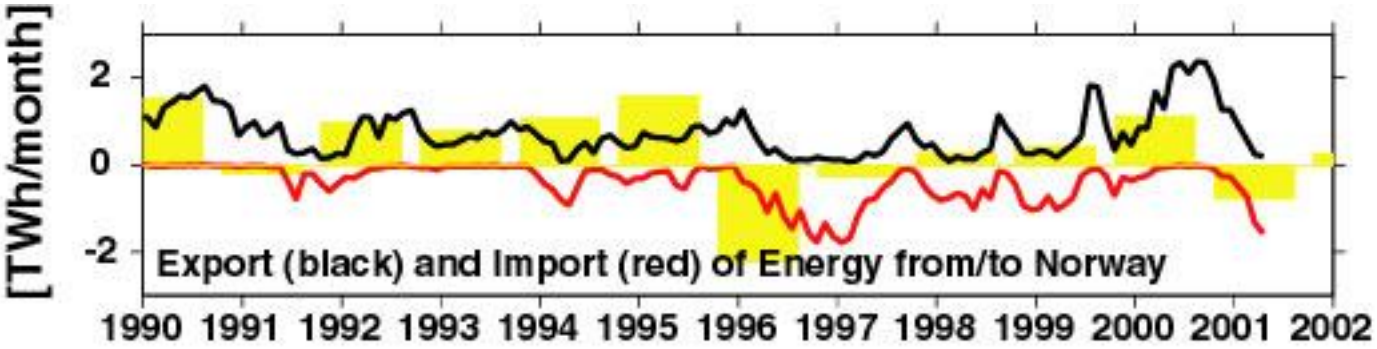
r = 0.7

1994-1995 off



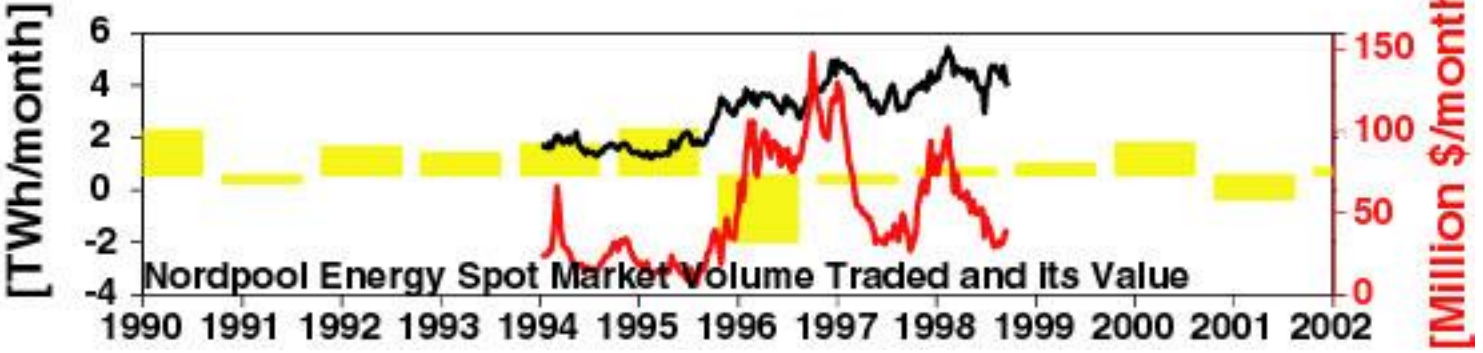
Deregulation and privatization in the 1990s allowed the establishment of the first international market for energy derivatives, called Nordpool.

Electricity trade in Norway



Electricity spot market price

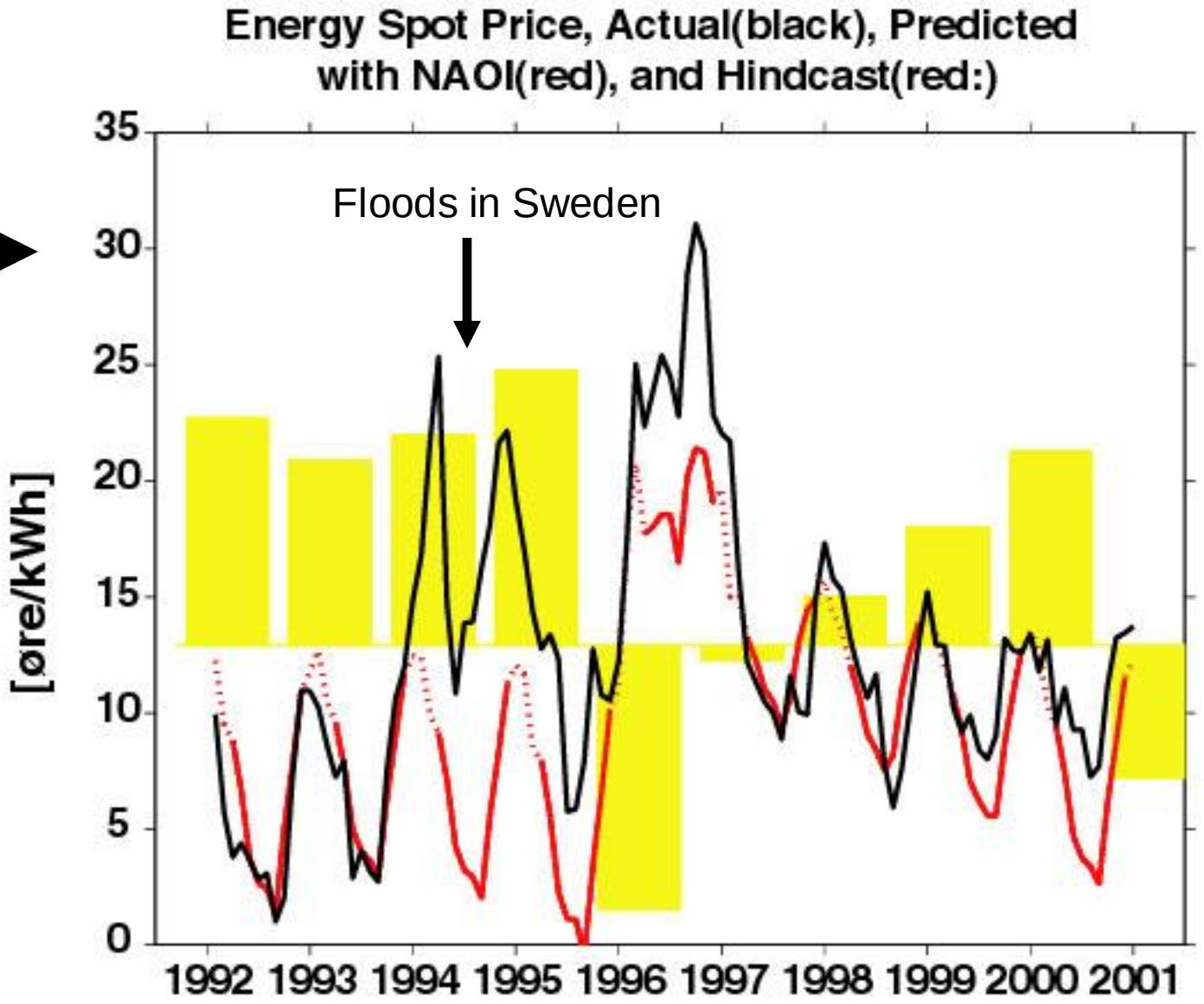
Spot volume traded and its value in dollars

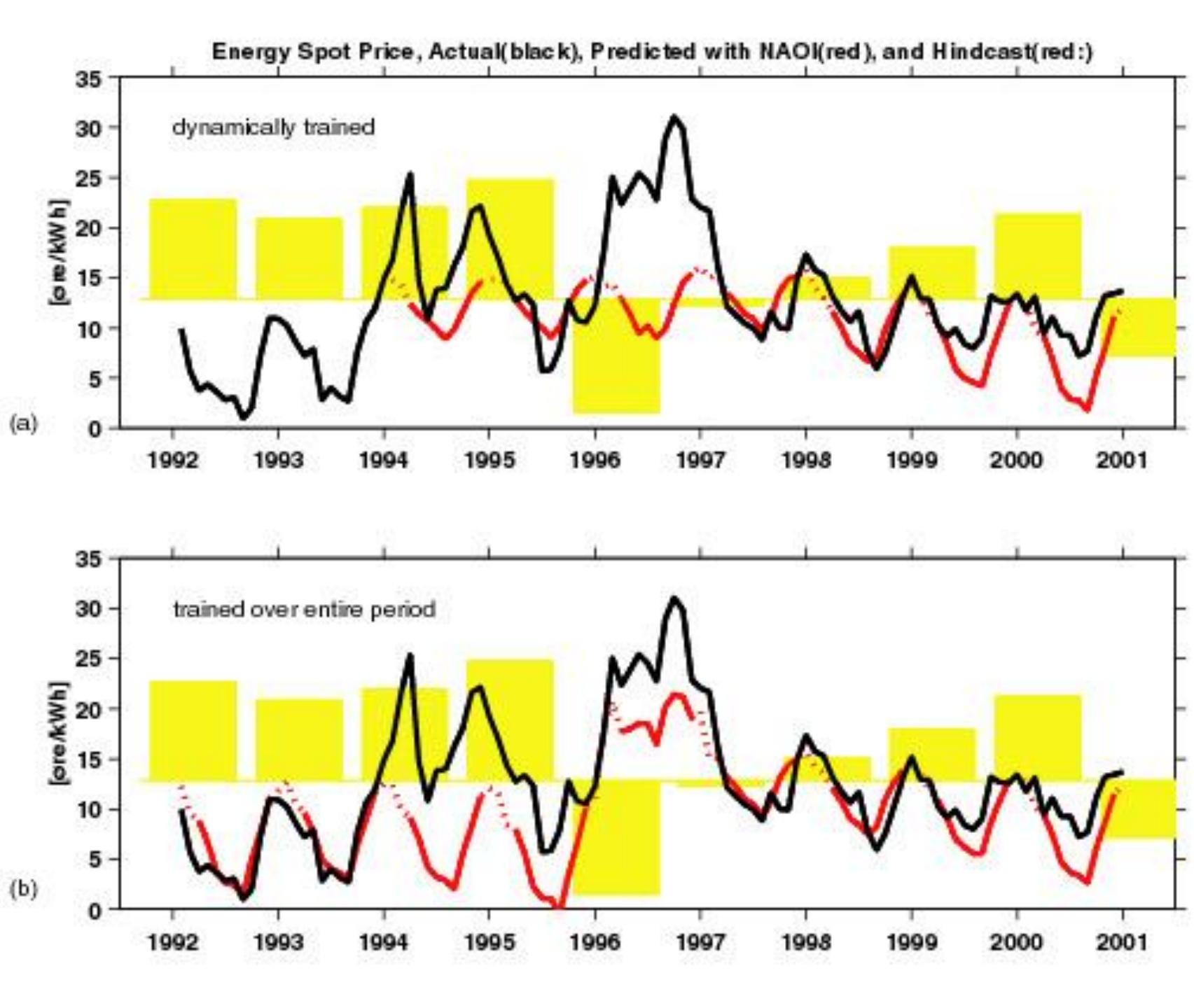


Correlation tests seem to support the proposed mechanism. Can the NAO Index then be used to predict spot prices?

Prices predicted solving Ax=b by regression

In this realization, I assumed regression coefficients are known, but not NAOI




Energy Spot Price, Actual(black), Predicted with NAOI(red), and Hindcast(red:)
dynamically trained
[øre/kWh]
(a)
trained over entire period
[øre/kWh]
(b)
0
5
10
15
20
25
30
35
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001

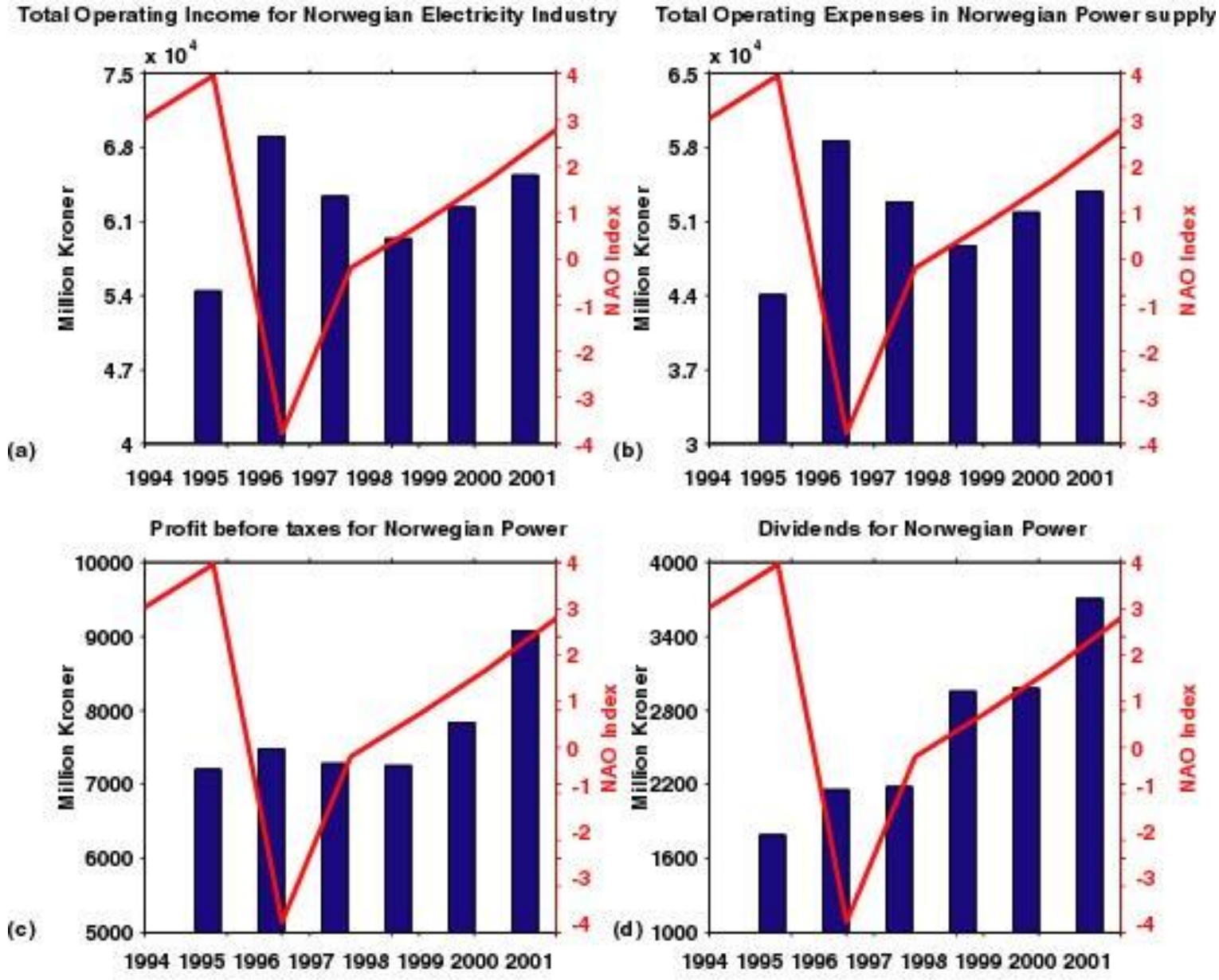
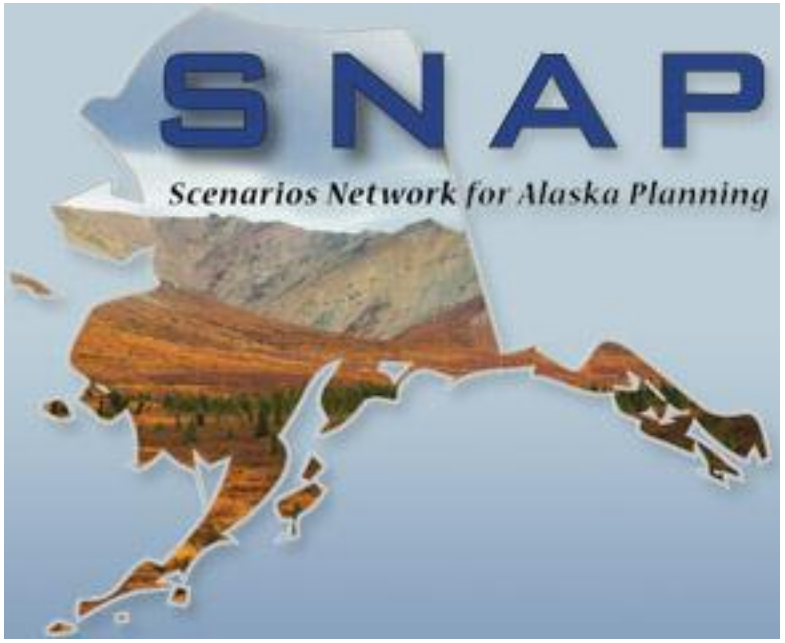


Figure 10a-f: Financial figures regarding the hydropower sector in Norway ploted against the NAO Index.

Climate Change

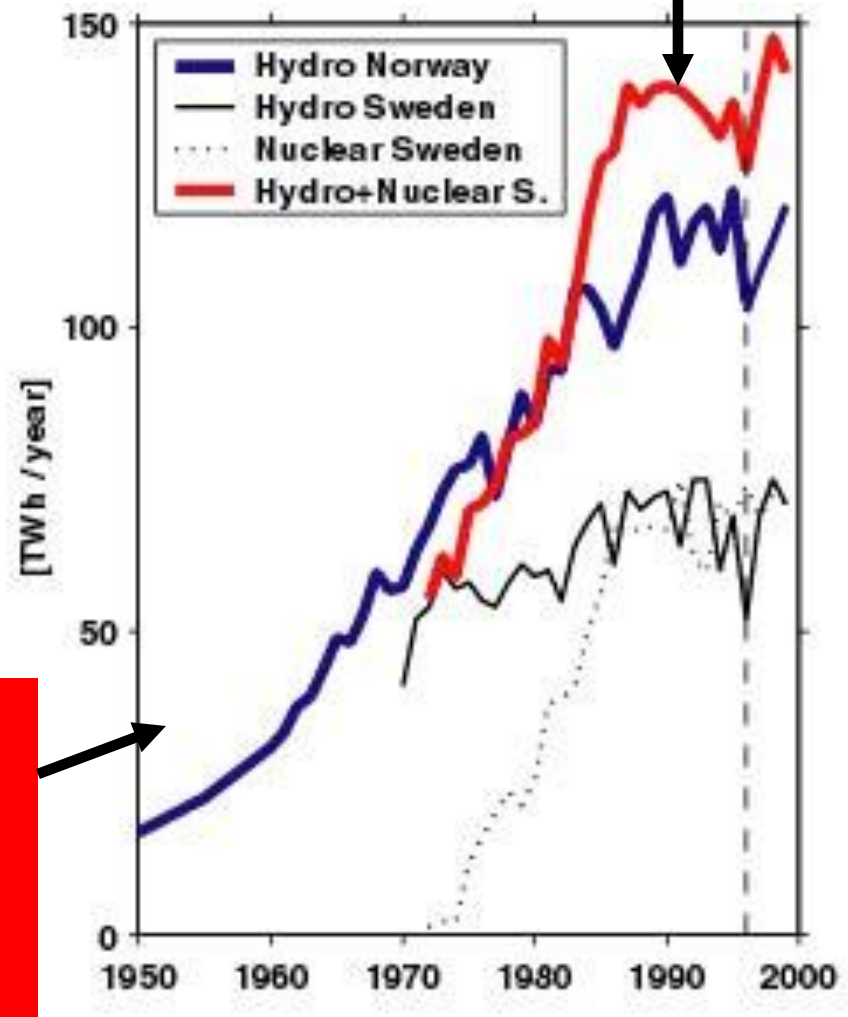
100-year and longer downscaled projections of temperature and precipitation for AK under various scenarios of Greenhouse Gas emissions

Projections of likely changes in soil temperatures, permafrost distributions and impact on groundwater storage



Energy production trends in Norway and Sweden

deregulation

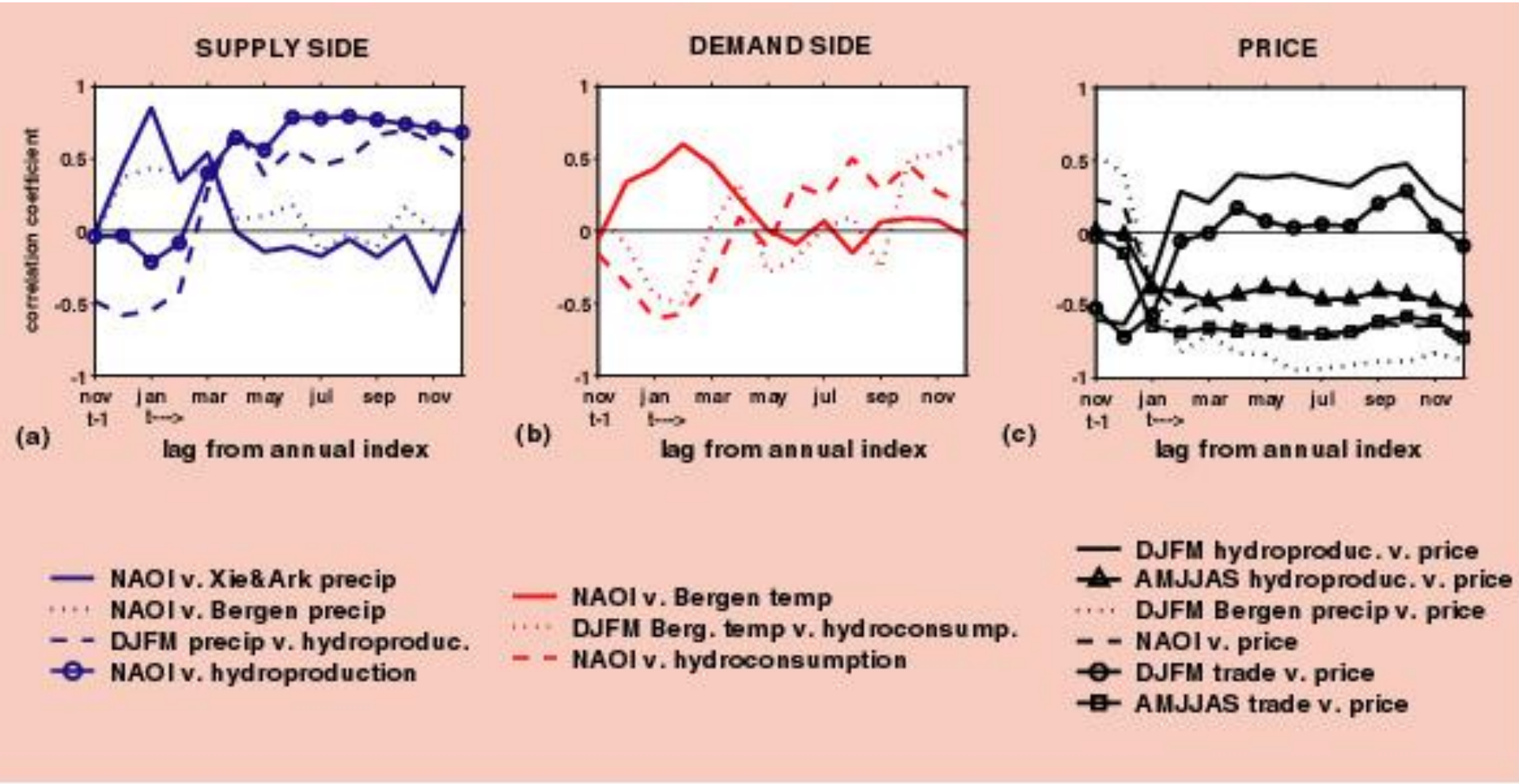


Trend, not related to NAO, Trade off

Energy supply in Norway and Sweden comes from only two sources, both which are climate dependent (directly or indirectly).

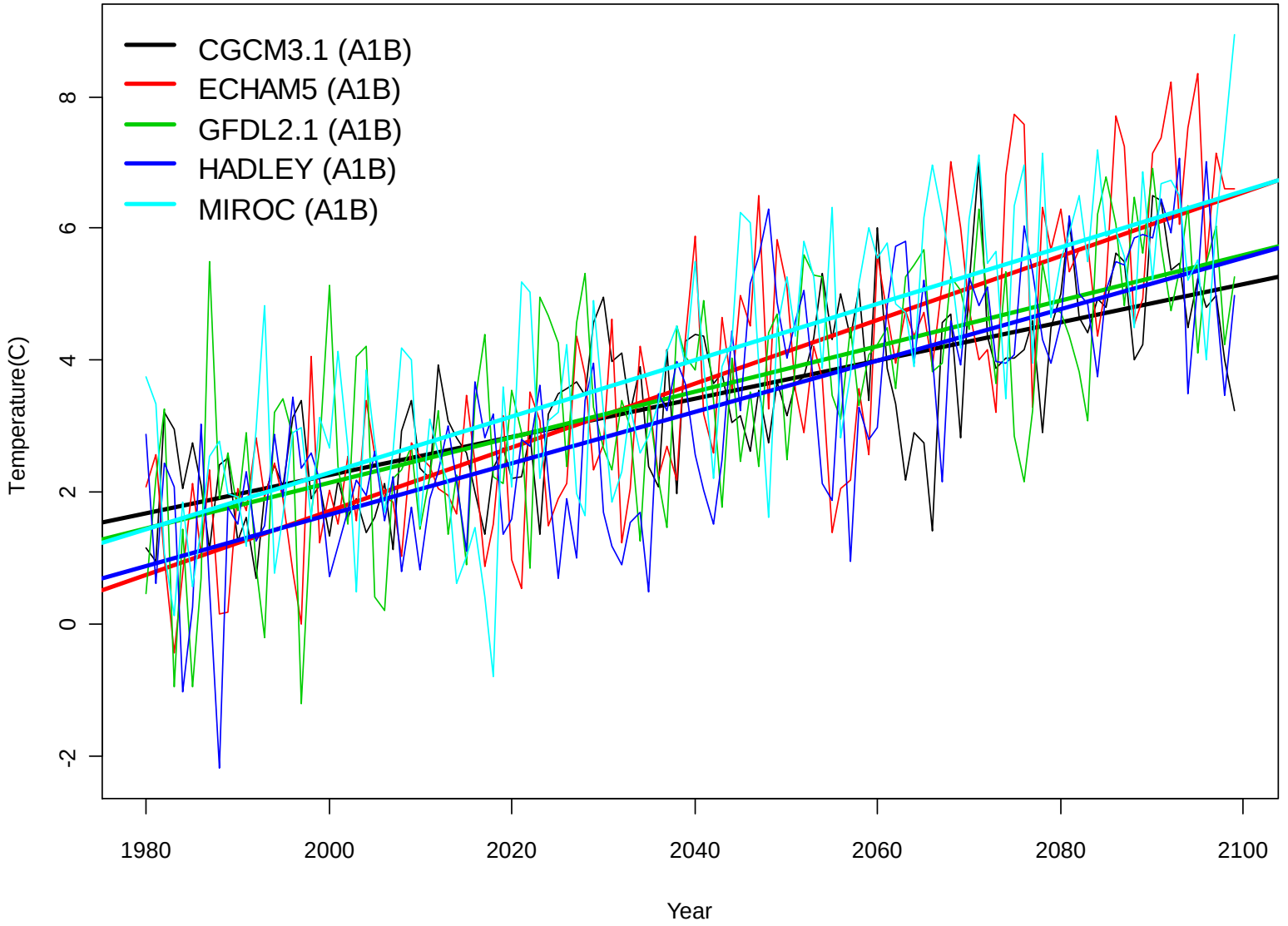
They share a physical power grid and an energy derivatives market.

They are each other's biggest trade partners for physical power.


SUPPLY SIDE
DEMAND SIDE
PRICE
correlation coefficient
1
0.5
0
-0.5
-1
nov
t-1
jan
t-->
mar
may
jul
sep
nov
(a)
(b)
(c)
lag from annual index
NAOI v. Xie&Ark precip
NAOI v. Bergen precip
DJFM precip v. hydroproduc.
NAOI v. hydroproduction
NAOI v. Bergen temp
DJFM Berg. temp v. hydroconsump.
NAOI v. hydroconsumption
DJFM hydroproduc. v. price
AMJJAS hydroproduc. v. price
DJFM Bergen precip v. price
NAOI v. price
DJFM trade v. price
AMJJAS trade v. price

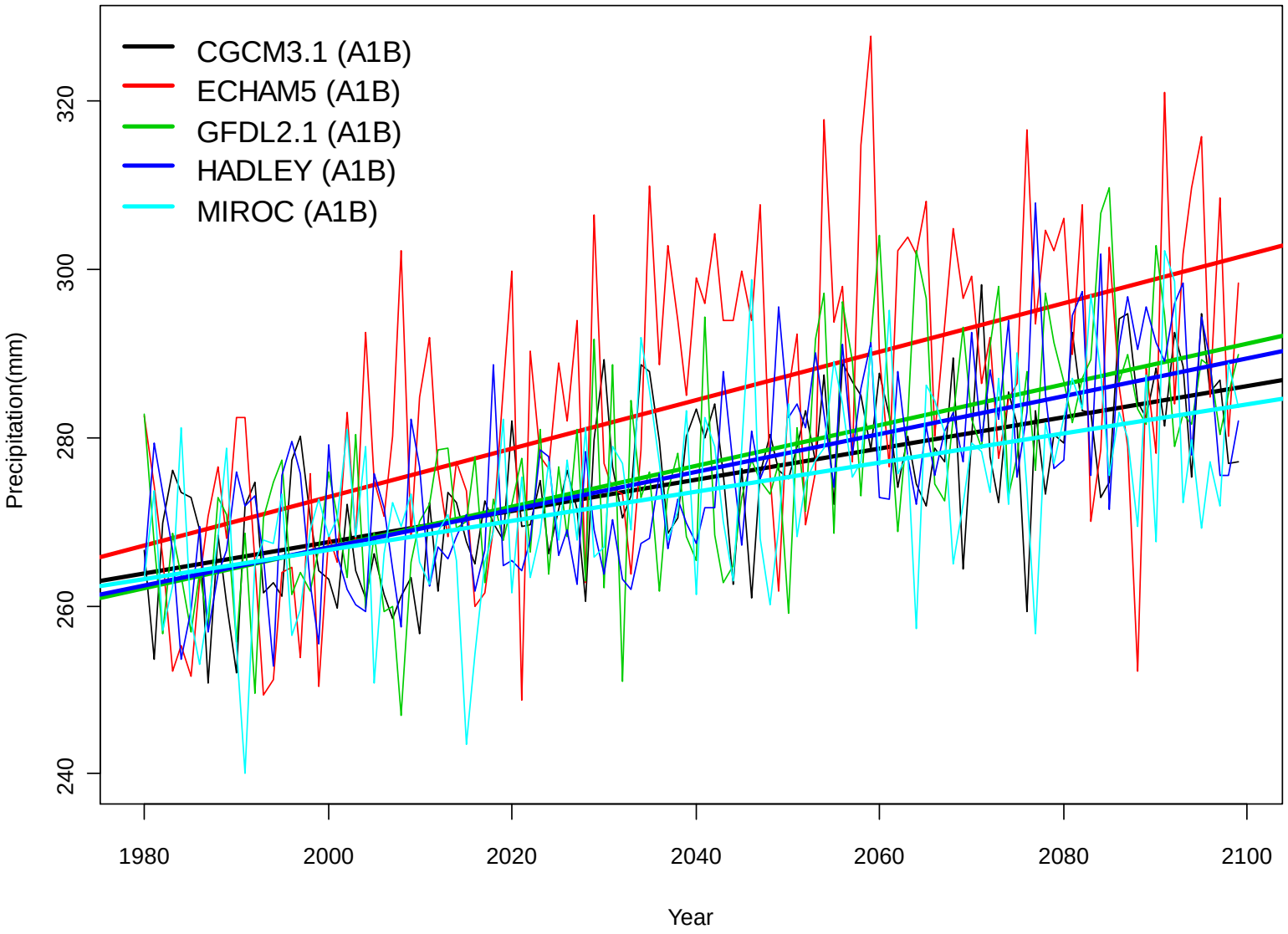
Temp Projections from SNAP for Southeast, AK

3.5-5.2 ° C/130 yrs



Precip Projections from SNAP for Southeast, AK

23-35 mm/130 yrs



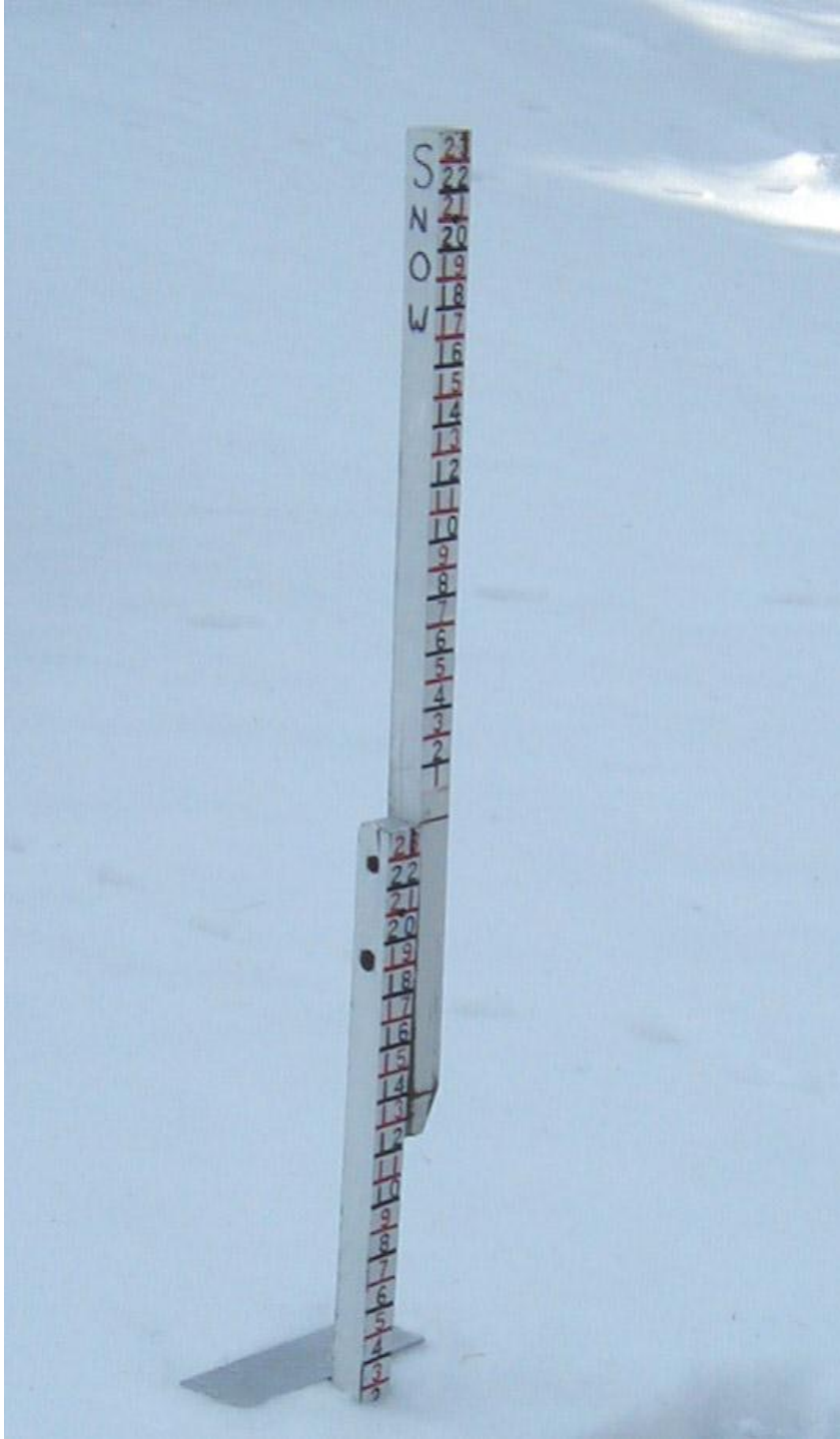
Other things to consider…

Monitoring!!!!!

Very little in SEAK, despite importance of hydropower. Compare to Norway

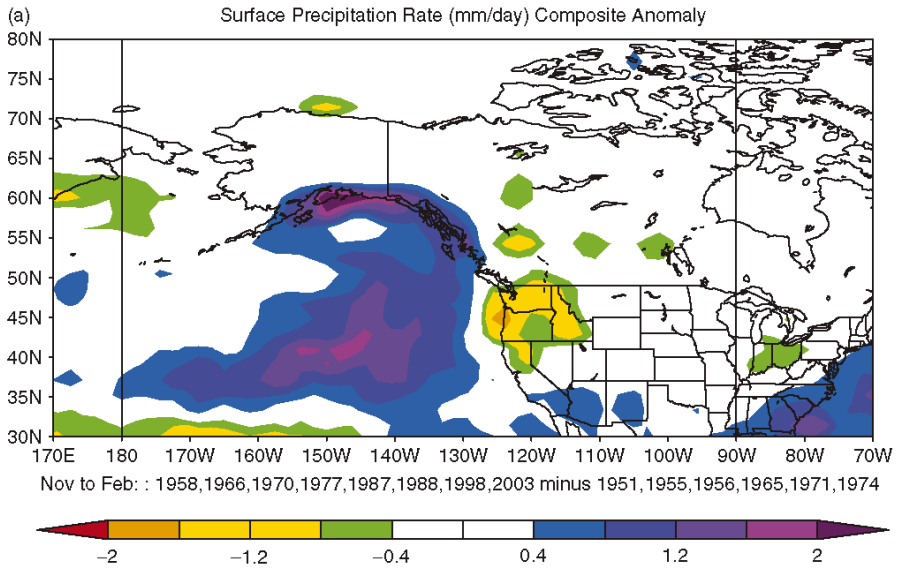
Temperature, Precipitation, Snow depth, ET, discharge, Glacier mass balance & change over time

AEL&P has USDA/NRSC Snotel site. Monitoring need not be costly!

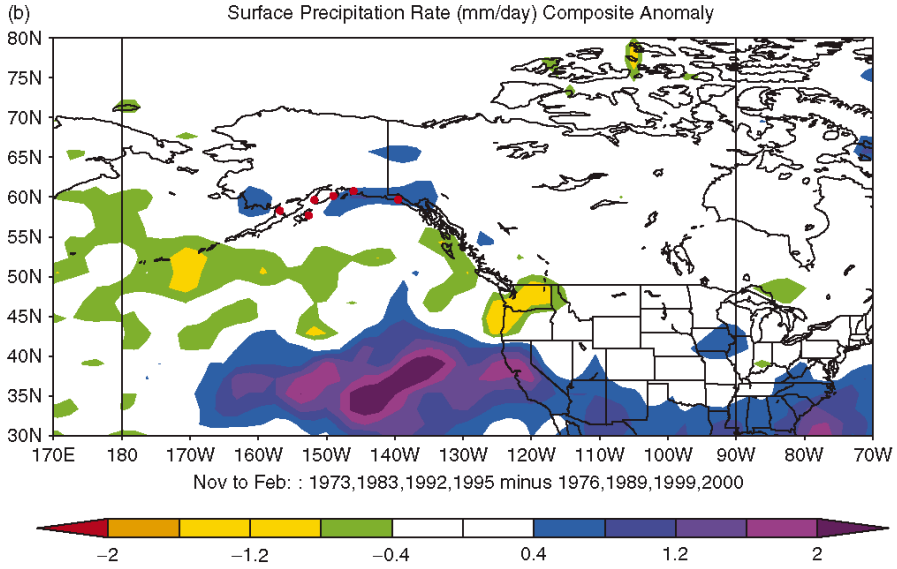


Difference Plots: precipitation

ElNino/AO-
minus
LaNina/AO-



ElNino/AO+
minus
LaNina/AO+



Bond and
Harrison, 2006

Big climate differences:

Most climate variability in Norway is explained by the NAO; climate variability in SEAK is more complex (a combo of multiple modes of variability)

ENSO driven variability in SEAK is predictable on a time scale that is meaningful for management, while NAO is not

Big economic differences:

Vastly different markets; Norway is a quasi state-run, internationally connected grid, SEAK is largely isolated run by very small municipalities and no obvious external market

Most of SEAK's tiny communities are saddled with high levels of debt service. Not the case in Norway, absorbed by the Federal economy

Norway's hydropower risk is commoditized, SEAK's is not. Maybe the ratepayers lose, regardless

In Norway, monitoring the snowpack is a management tool. SE doesn't use snowpack monitoring.

Lessons for Susitna:

Regional Market Integration matters

Climate mechanisms matter…especially the potential for tipping points such as change in glacier distribution

The tools already exist to improve risk management considerably; need more training in use of seasonal forecasting

Bottom line

- Climate Change DOES matter, but our short observational records in Alaska make it difficult to separate climate change from natural multi-decadal variability. (Attribution problem). There are also data quality problems, especially for measurements of precipitation and discharge
- Based on our short record and a small number of studies, about half of the observed climate change in Southeast may be attributable to long-term climate change and about half may be attributable to natural climate variability on decadal and multi-decadal timescales

Bottom Line

- There is high inter-annual variability in climate conditions throughout SEAK. Less than 25% of this is explainable by ENSO or PDO conditions! Other dynamics, i.e. PNA, AO, and random variability are also factors
- However, seasonal prediction is more accurate in SEAK than most parts of the U.S. This is the effect of PDO persistence, steady long-term warming, and variance explained by ENSO, which is typically predictable 6-9 months in advance

Bottom Line: Recommendations

- Expanded/improved observational networks of temperature, precipitation/snow, runoff, and ET, especially at higher altitudes
- Combined with Climate Change Projections and
- Seasonal Prediction
- Will decrease risk in hydroelectric power management and planning for SEAK

Talking Points

- Climate drivers in Alaska and the Arctic and how they impact hydropower
- Long-term climate change versus climate variability on interannual, decadal, and longer timescales
- Predictive tools: useful for management

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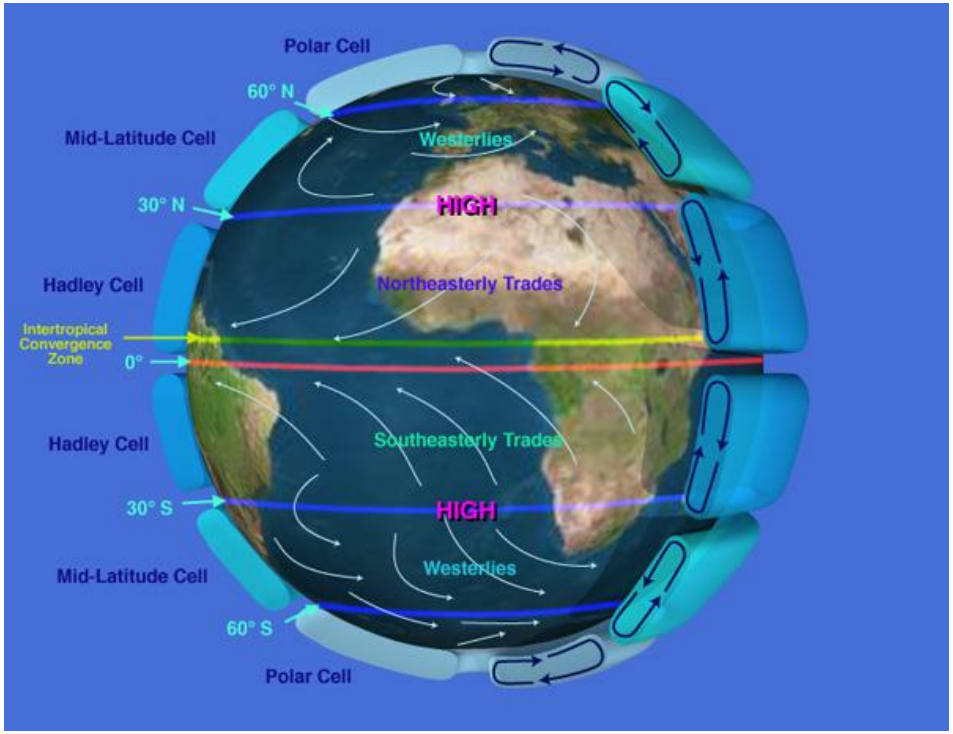
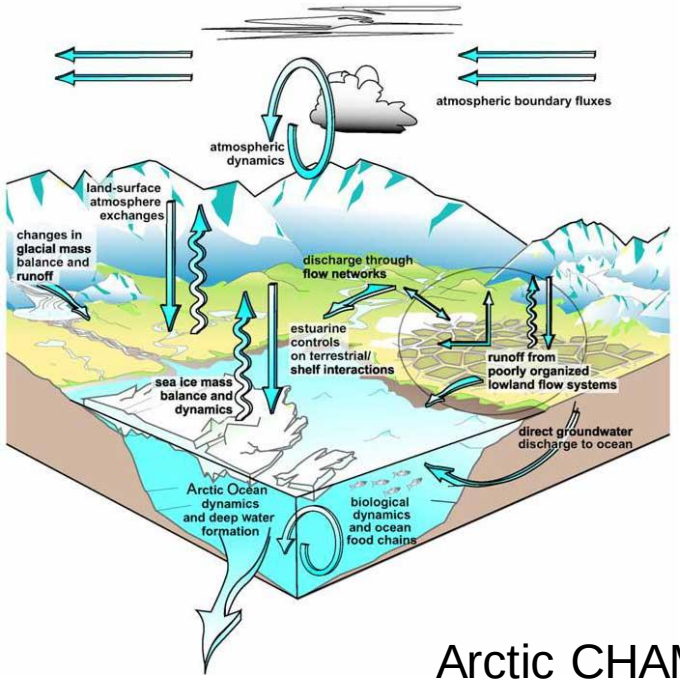
Talking Points

- Climate drivers in Alaska and the Arctic and how they impact hydropower
  - Large scale global ocean atmosphere circulation



Talking Points

- Climate drivers in Alaska and the Arctic and how they impact hydropower
  - Large scale global ocean atmosphere circulation
  - Regional 'quick' feedbacks from ice edge, snow cover, Aleutian Low/Siberian High or Icelandic Low/Azores High
  - Regional 'slow' feedbacks from glaciers and permafrost (though catastrophic change can occur quickly)



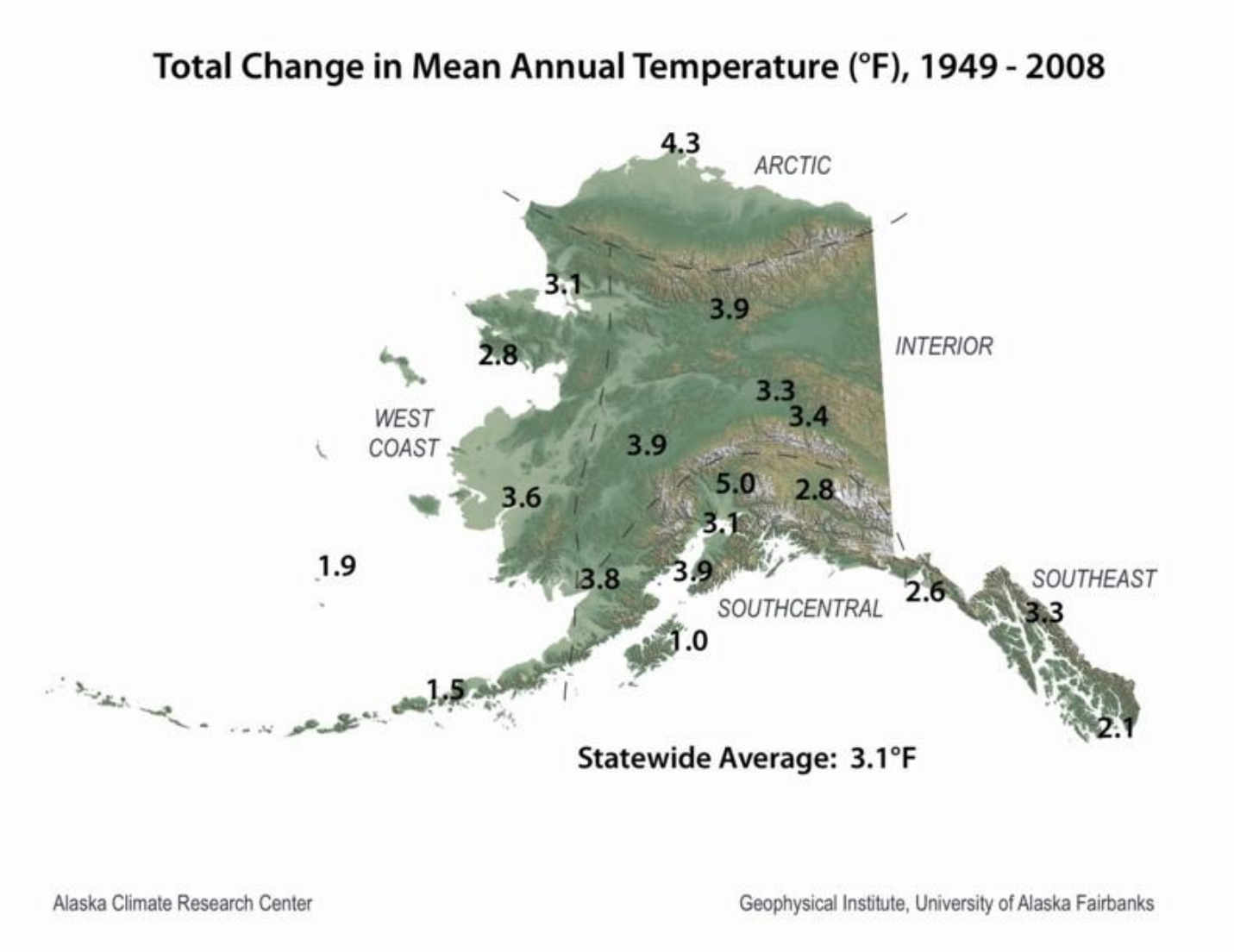
Arctic CHAMP

Talking Points

- Climate drivers in Alaska and the Arctic and how they impact hydropower
- Long-term climate change versus climate variability on interannual, decadal, and longer timescales
- Predictive tools: useful for management

Climate Change

Observed Temperature Change in Alaska



Observed Temperature Change by Season

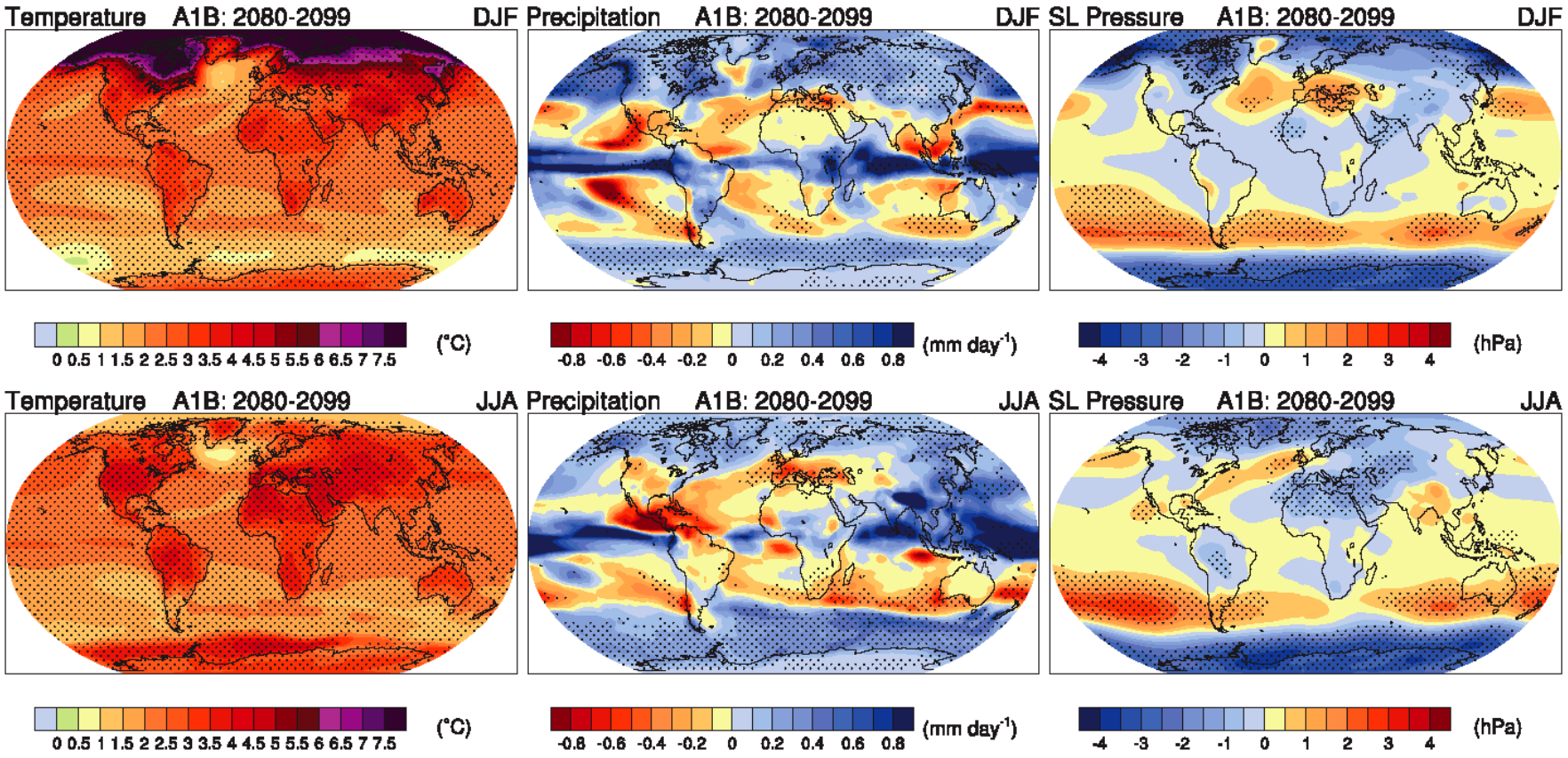
Total Change in Mean Seasonal and Annual Temperature (°F), 1949 - 2008

Region	Location	Winter	Spring	Summer	Autumn	Annual
Arctic	Barrow	6.5	4.4	2.8	3.4	4.3
Interior	Bettles	8.5	4.6	1.8	1.1	3.9
	Big Delta	9.2	3.5	1.2	-0.2	3.4
	Fairbanks	7.7	3.8	2.3	-0.4	3.3
	McGrath	7.4	4.8	2.7	0.6	3.9
West Coast	Kotzebue	6.6	1.8	2.5	1.6	3.1
	Nome	4.4	3.6	2.5	0.6	2.8
	Bethel	6.6	5.0	2.3	0.1	3.6
	King Salmon	8.1	4.7	1.8	0.6	3.8
	Cold Bay	1.5	1.8	1.8	0.9	1.5
	St Paul	1.0	2.4	2.8	1.3	1.9
Southcentral	Anchorage	6.8	3.6	1.6	1.4	3.1
	Talkeetna	8.9	5.4	3.1	2.4	5.0
	Gulkana	8.1	2.4	0.9	0	2.8
	Homer	6.3	4.0	3.4	1.7	3.9
	Kodiak	0.9	2.3	1.2	-0.4	1.0
Southeast	Yakutat	4.9	3.1	1.8	0.3	2.6
	Juneau	6.6	3.1	2.1	1.4	3.3
	Annette	3.9	2.5	1.7	0.2	2.1
	Average	6.0	3.5	2.1	0.9	3.1

Alaska Climate Research Center

Geophysical Institute, University of Alaska Fairbanks

Projected temperature, precipitation, and pressure changes



IPCC AR4, 2007

Climate Variability

Talking Points

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- Long-term climate change versus climate variability on interannual, decadal, and longer timescales
- Predictive tools: useful for management

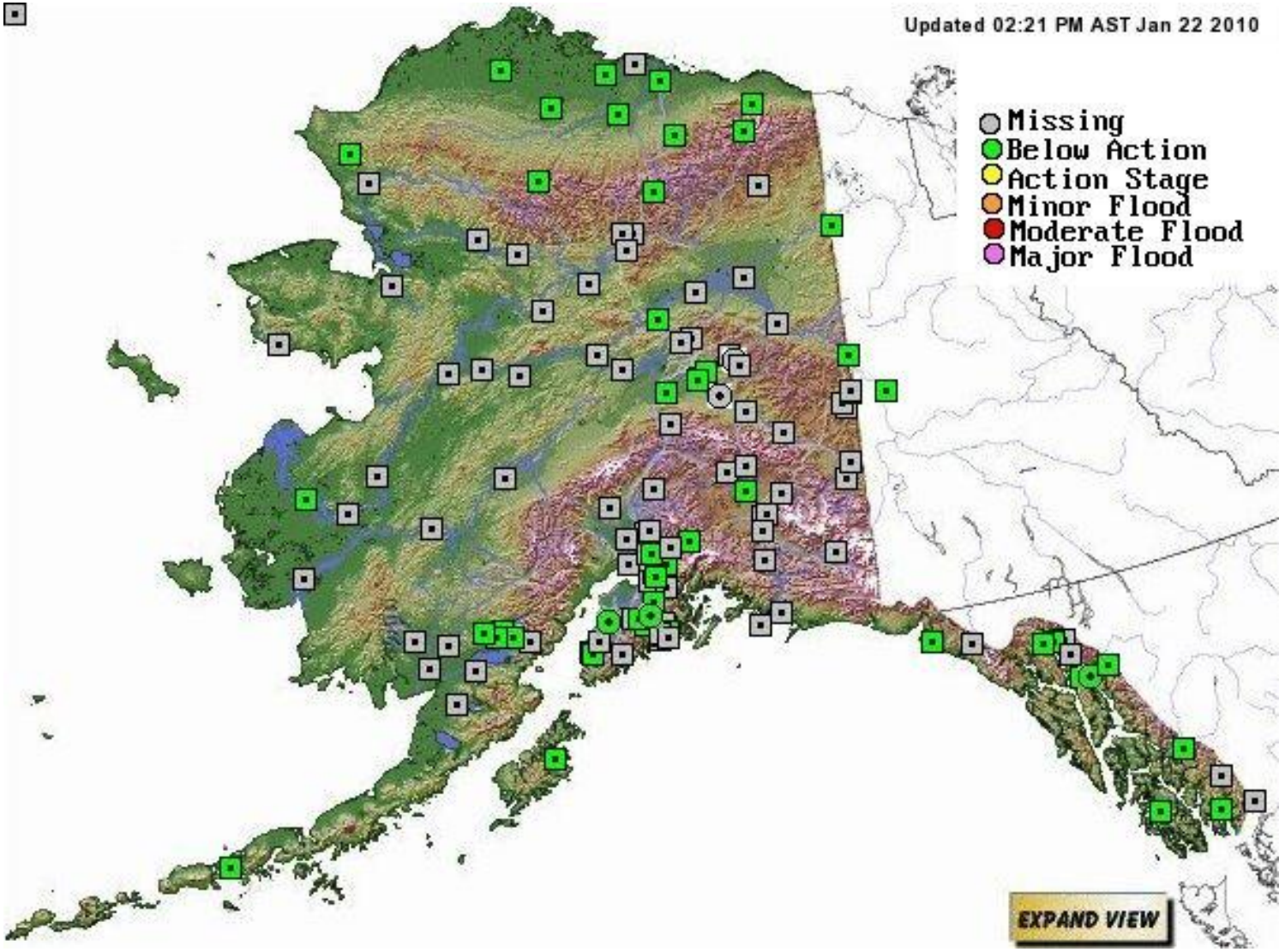
Talking Points

- Predictive tools: useful for management
  - Short term numerical weather prediction
  - Probabilistic seasonal forecasts
  - Longterm climate projections

Talking Points

- Predictive tools: useful for management
  - Short term numerical weather prediction
  - Probabilistic seasonal forecasts
  - Longterm climate projections

NWS RFC Alaska-Pacific



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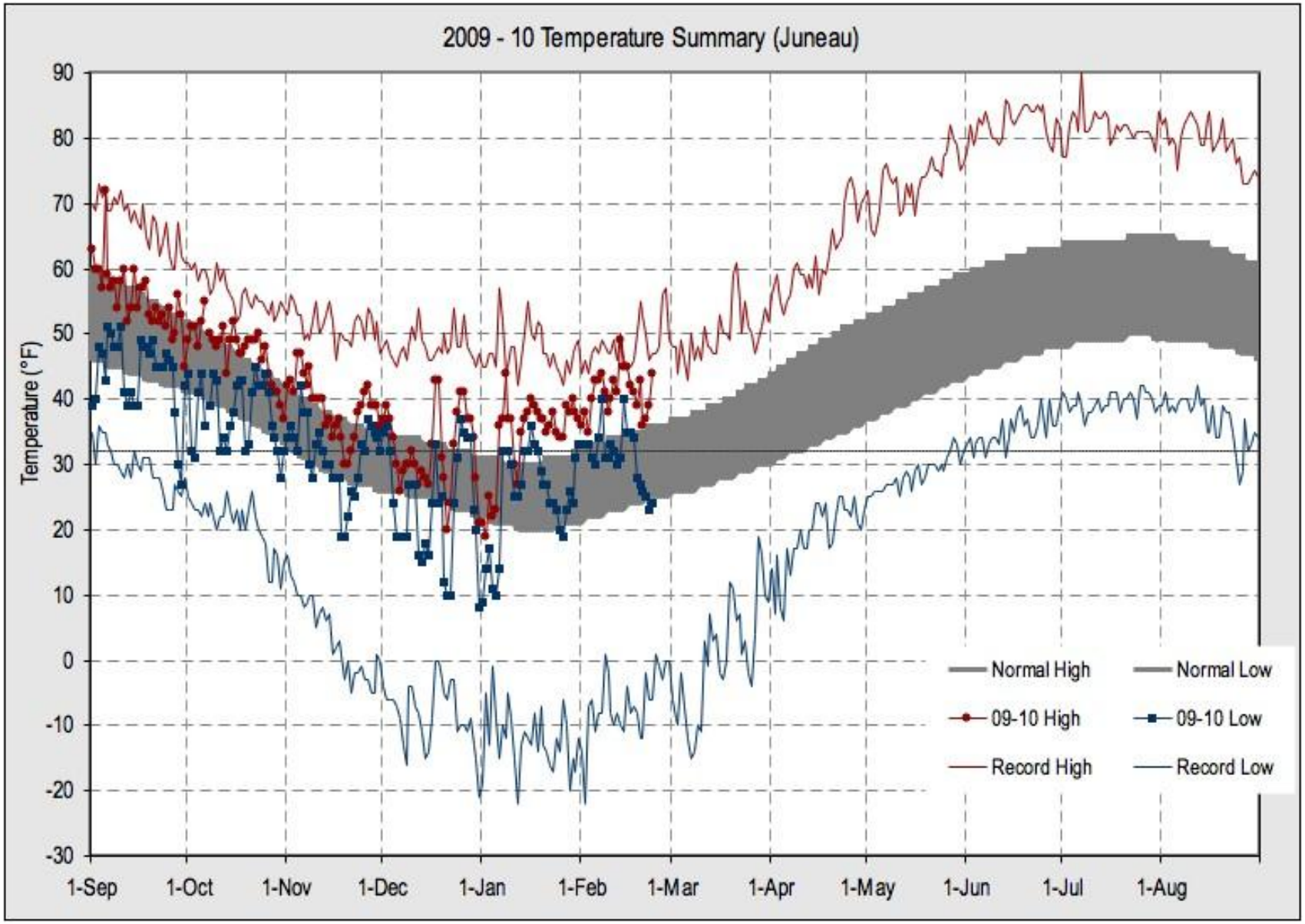
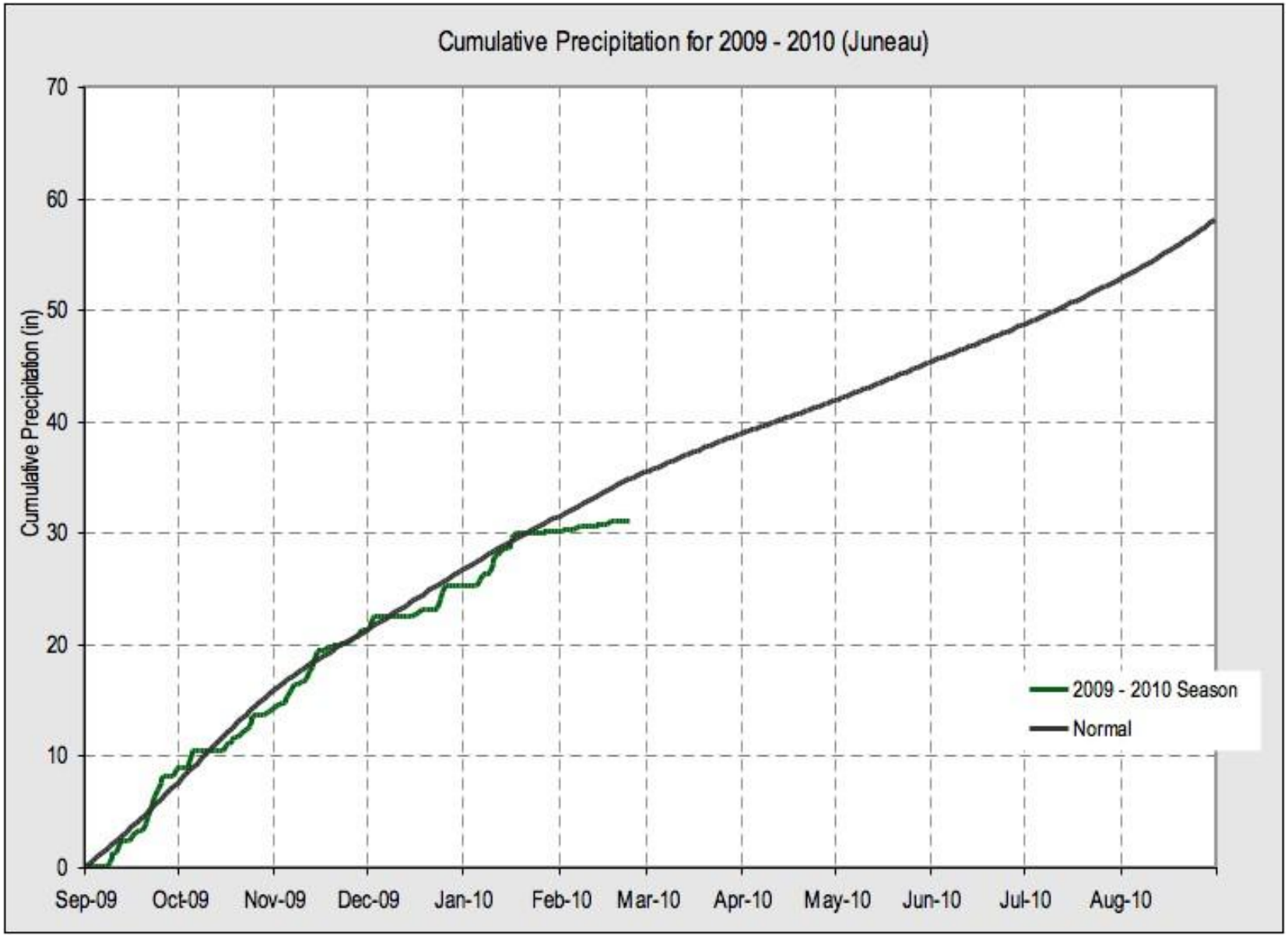
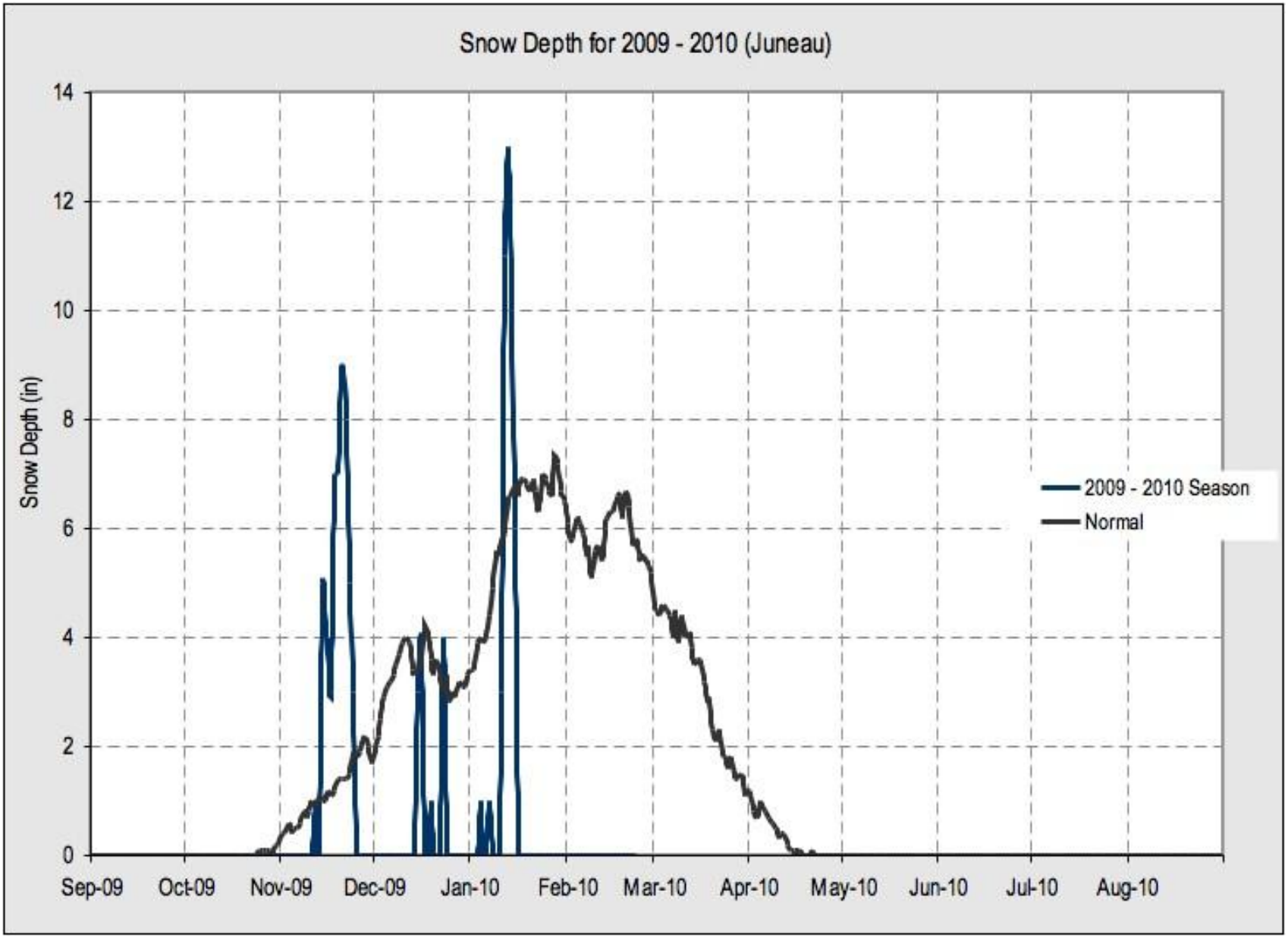
Juneau Climate Anomalies



Juneau Climate Anomalies



Juneau Climate Anomalies



SE Grid – Existing and Proposed

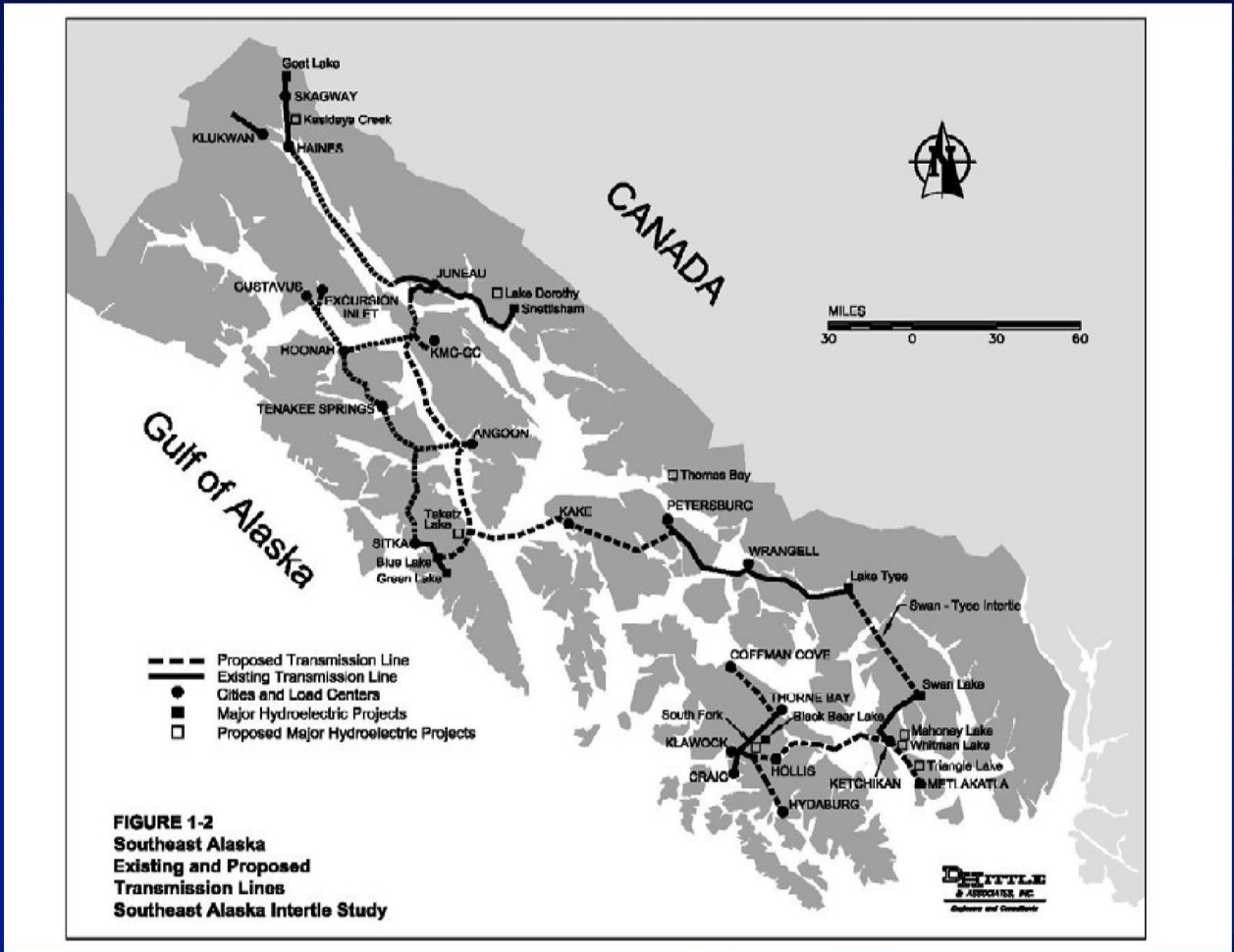


FIGURE 1-2
Southeast Alaska
Existing and Proposed
Transmission Lines
Southeast Alaska Intertie Study

The FOUR DAM POOL Power Agency