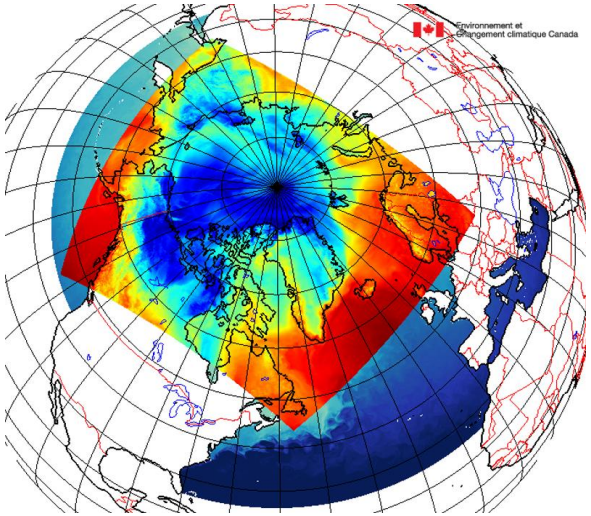
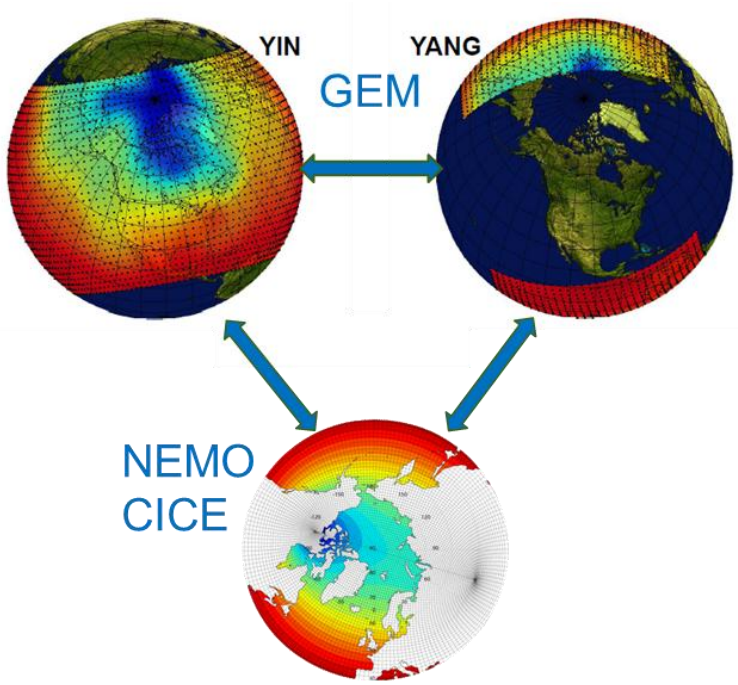
Unclassified - Non-Classifié

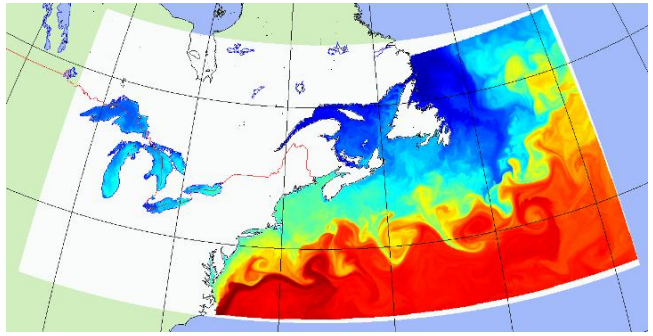
Coupled Atmosphere-Ice-Ocean Prediction Systems at Environment and Climate Change Canada

G.C. Smith, J.-P. Paquin, P. Blain, B. Casati, F. Davidson, F. Dupont, J.-F. Lemieux, S. MacDermid, D. Paquin-Ricard, K. A. Peterson, M. Plante, F. Roy

DA-TT/CP-TT Workshop (Oct. 26-30, 2026)





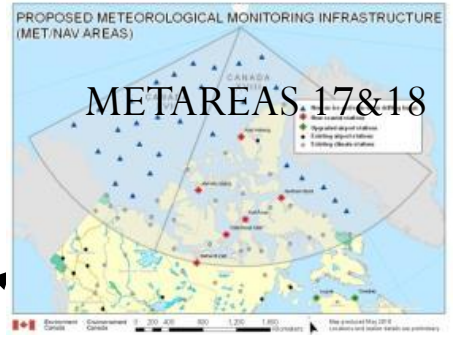


ECCC Coupled Prediction Users and Applications



DFO Applications

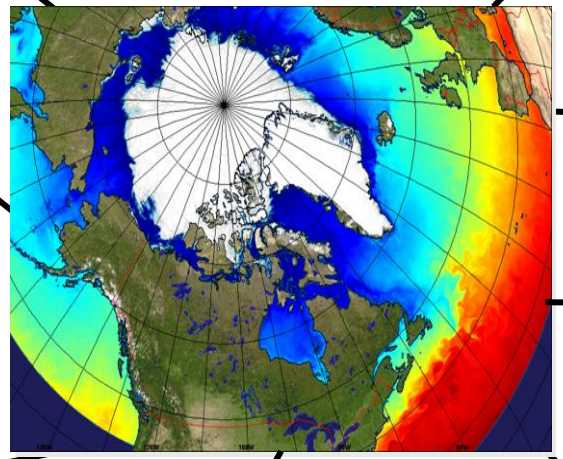
- Fisheries and Aquaculture management
- Ocean climate monitoring
- Marine Protected Areas





DND Applications

- Situational awareness
- Anti-submarine warfare
- Operational support

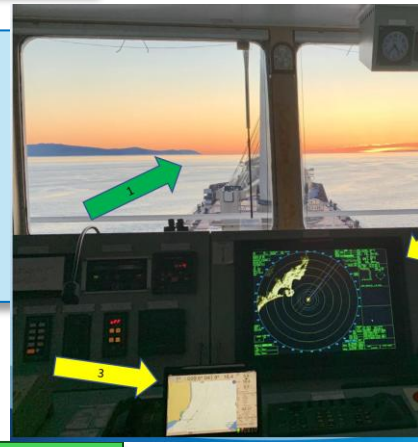


Canadian Ice Service Operations

- High-pressure ridges
- Automated analyses
- Iceberg drift

E-NAVIGATION Dynamics Maps

- **Currents, sea surface height**
- **Waves, wind, ice**





Canadian Coast Guard

- Search and Rescue
- Environmental Emergency Response



National Environmental Emergency response Centre (NEEC)

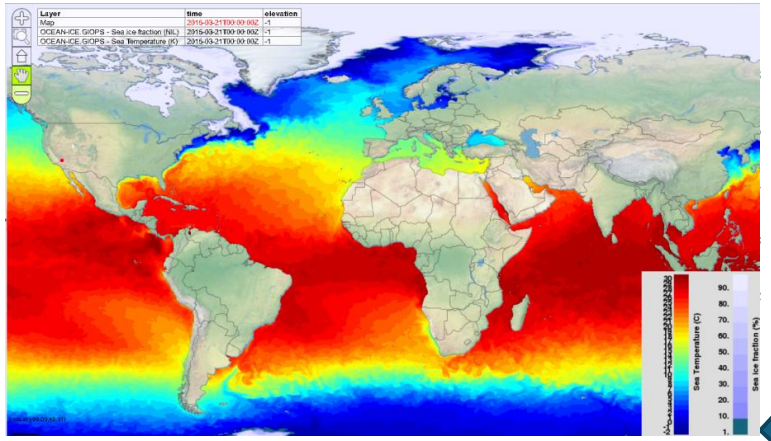
- Oil spill

Marine NWP services

- NWP, waves, storm surge
- Air-sea-ice interactions and feedbacks

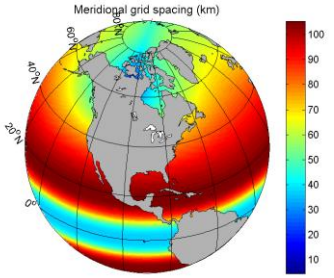
Ice-ocean forecasting with NEMO + CICE

Operational
Experimental

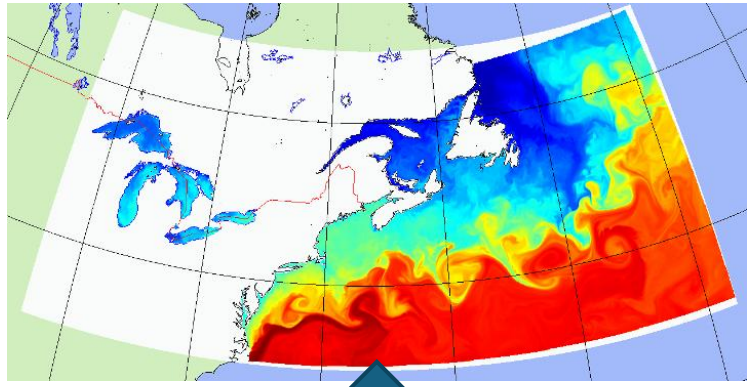


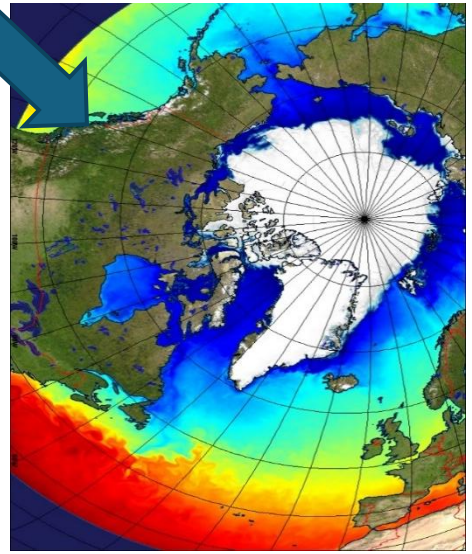
GIOPS: 1/4°Global, Coupled to GDPS (10day) and GEPS (16day and monthly)

Seasonal 1°

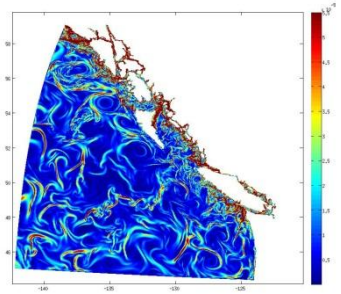


Water Cycle Prediction System
Great Lakes 1km+East Coast (1/36 °)

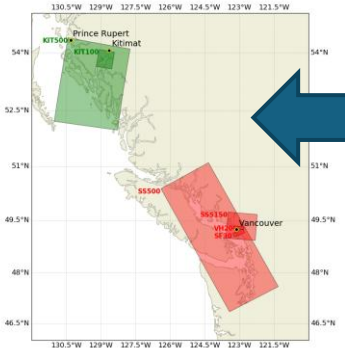




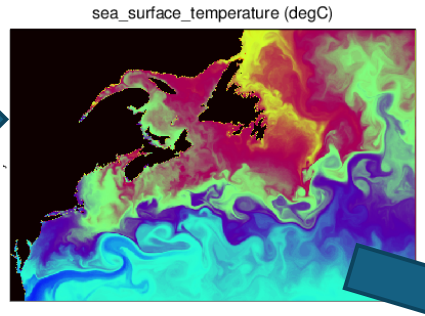
RIOPS: Regional 1/12°
CAPS Coupled (3km atm)



CIOPS-W: Northeast Pacific 1/36° + 500m
Salish Seas

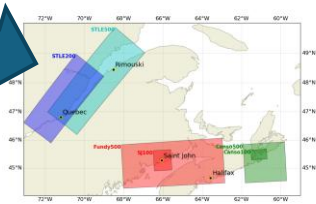


POPS: Kitimat, Fraser River and Vancouver Harbour



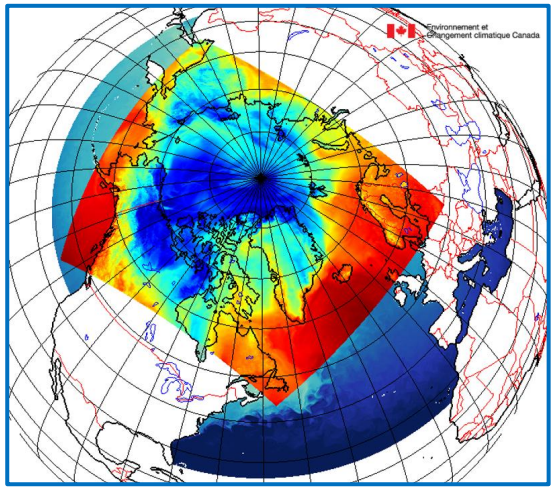
CIOPS-E: Coastal East Coast 1/36°

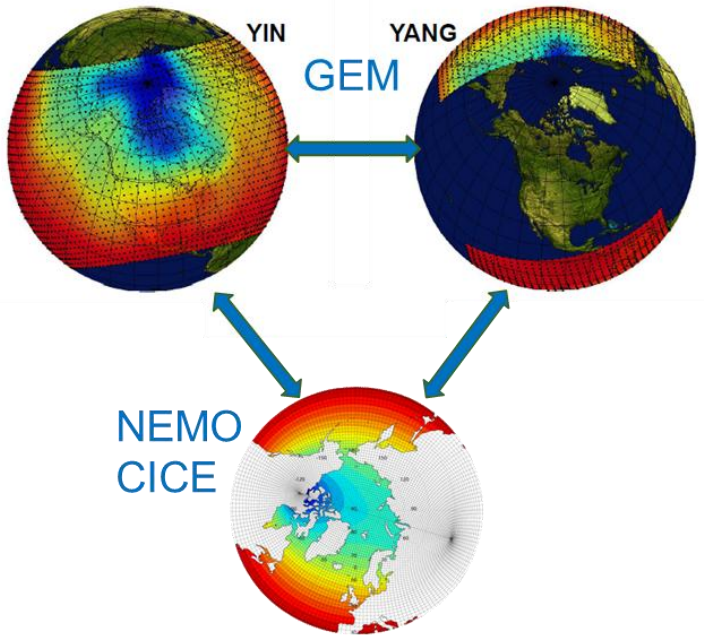
POPS: St. Lawrence Estuary, St. John and Canso Harbours



ECCC Coupled Forecasts

- Coupled Global Medium-range Deterministic System
  - 10d forecasts (with hybrid ML model)
- Coupled Global Ensemble Forecasts
  - 15d (daily) and 32d (weekly) forecasts
- Seasonal Predictions (CanSIPS)
  - 12-month forecasts
- Water Cycle Prediction System (WCPS)
  - Great Lakes and East Coast, 48h forecasts
- Canadian Arctic Prediction System (CAPS)
  - Pan-Arctic high-resolution 48h coupled forecasts





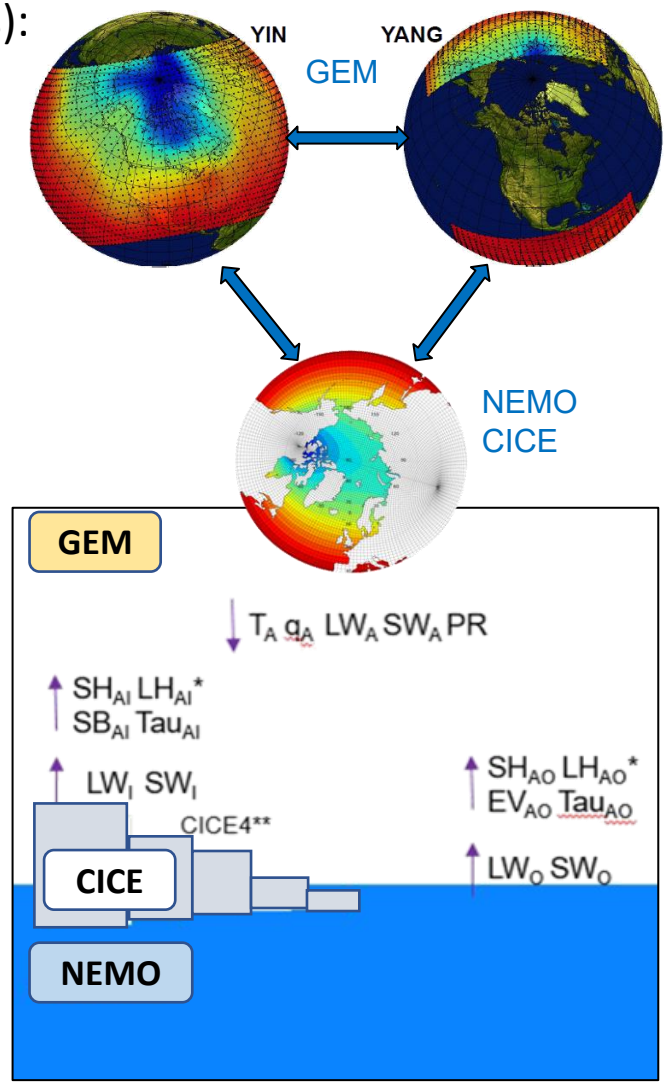
Coupled GEM-NEMO-CICE systems

In coupled GEM-NEMO-CICE systems, (e.g., Great Lakes model, Global (GDPS), seasonal systems):

- Evolution of water and sea-ice properties over oceans and Great Lakes is modeled by 3D thermodynamic ocean (NEMO) and sea-ice (CICE) models *coupled* to GEM

- **NEMO+CICE are coupled to GEM** at every *common* time step (NEMO+CICE step >> GEM step) using a flux coupling approach based on common shared atm., oceanic, and ice state variables:
  - bidirectional transfer of momentum, heat, and moisture at the snow–ice and ocean surface -> allows interactive & consistent transfers
  - NEMO+CICE receive downward radiative fluxes (LW,SW) and state variables (TT,HU,PR) from GEM
  - GEM receives outgoing surface layer atmospheric fluxes and upward LW fluxes based on ice+ocean properties simulated by NEMO+CICE

- **GEM-NEMO-CICE** coupling allows representation of complex and dynamic interactions between the atmosphere, oceans and ice such as
  - Tropical cyclones, hurricanes, typhoons
  - Coastal polynyas, leads, fluxes through the ice (ITD)



Coupled GEM-NEMO-CICE

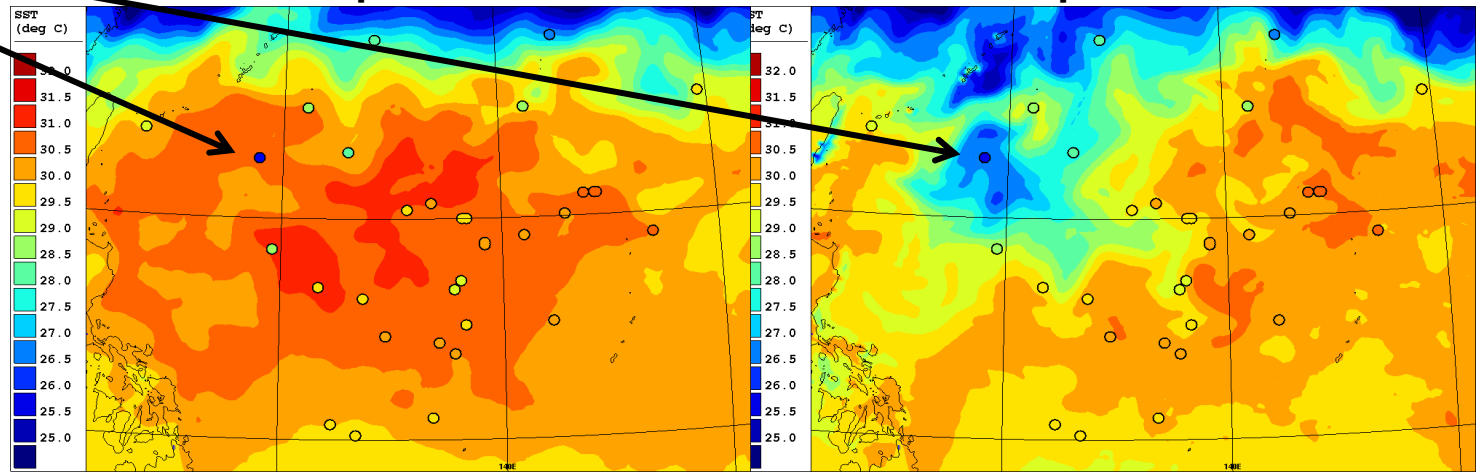
SST from drifter obs.
Much better agreement of cold wake in Coupled forecasts

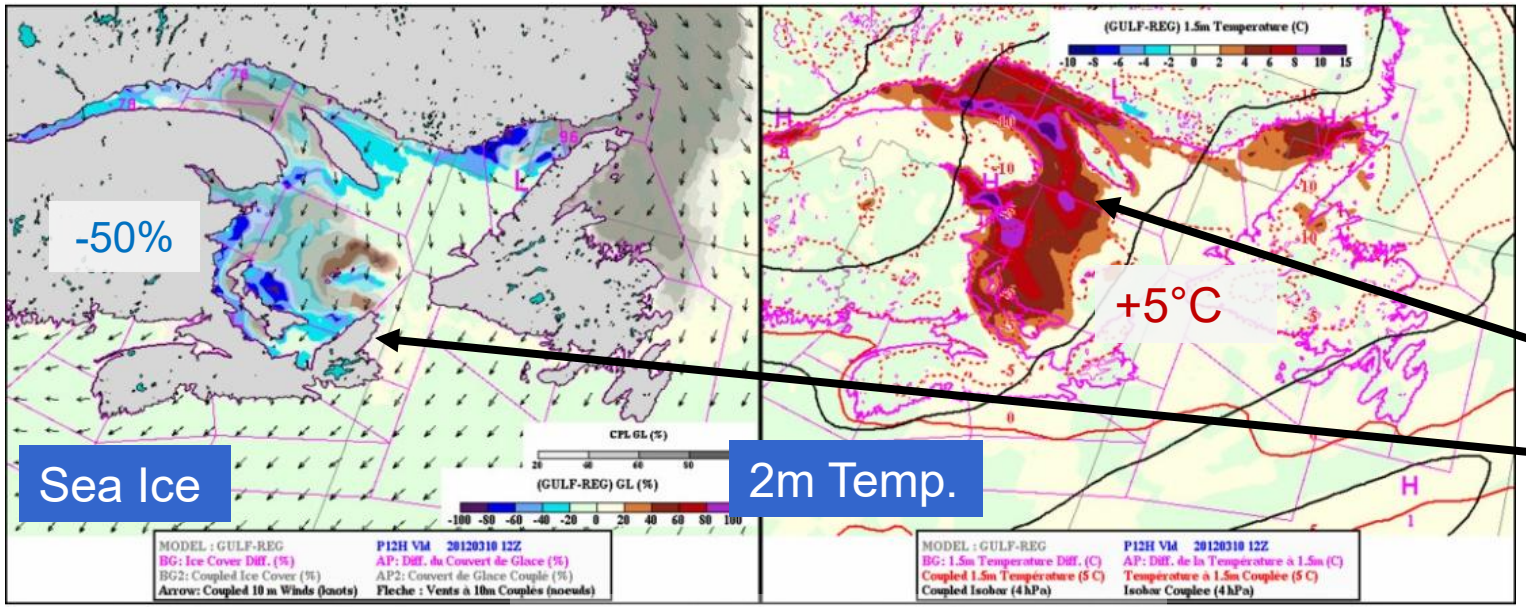
Smith et al., 2018, MWR

Impact of Coupled Forecasts for Typhoon Neoguri

96h forecasts, valid 00Z, July 10, 2014

Uncoupled SST | **Coupled SST**





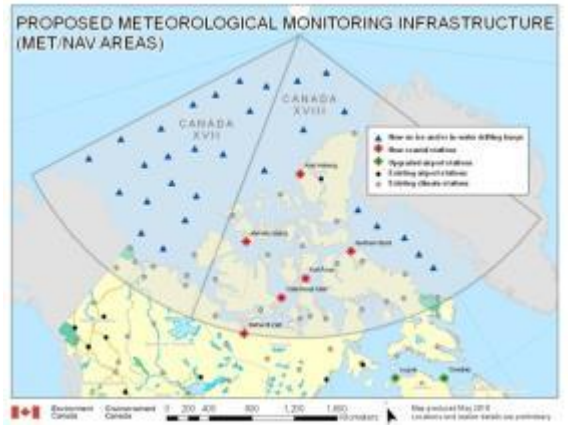
Valid for Mar. 10, 2012, 12Z

Coupled – Uncoupled differences
Gulf of St. Lawrence (GSL)
Coupled Forecasting System

Reproduced following Pellerin et al. (2004)

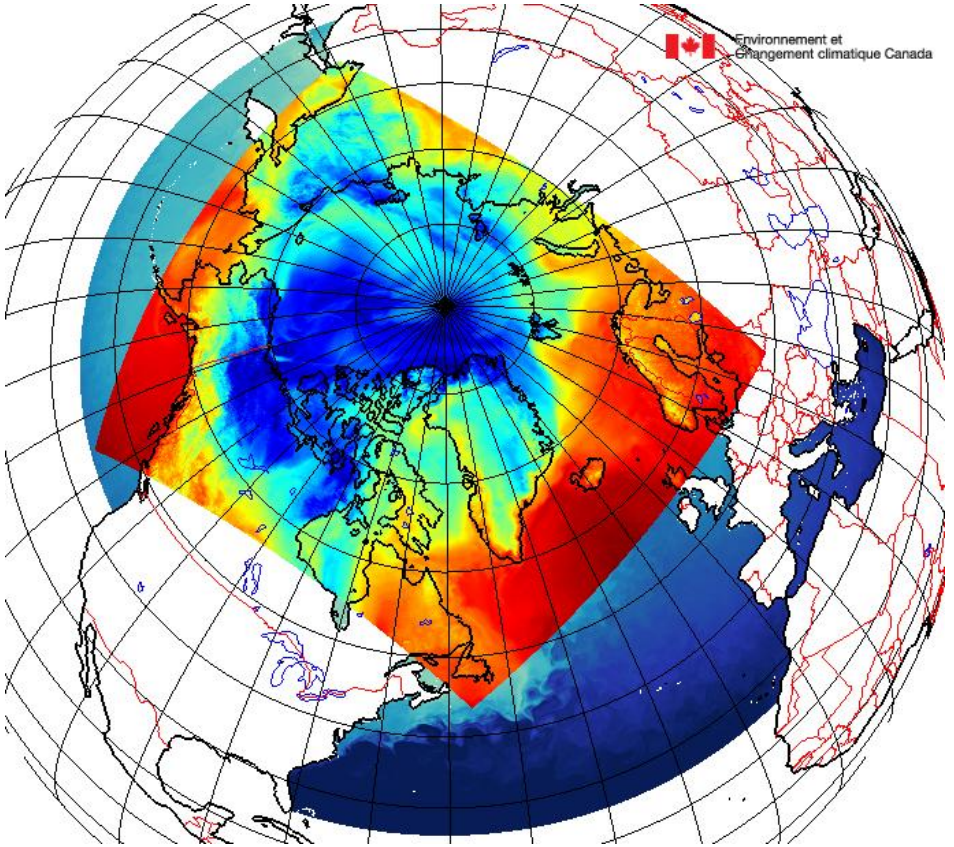
Canadian Arctic Prediction System (CAPS)

High-resolution coupled atmosphere-ice-ocean prediction system



- In support of :
  - Weather prediction for northern Canada
  - EC METAREAs Services
  - Marine emergency response
  - National Defense Operations

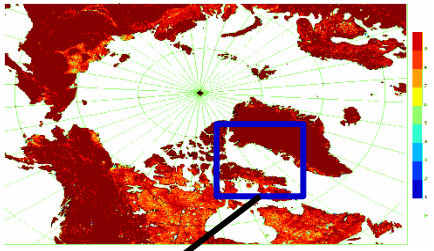
- Coupled atmosphere-ice-ocean model
  - Ice-ocean: NEMO-CICE (3-8 km)
    - Tides, landfast ice
  - Atmosphere: GEM (3 km)
    - Predicted particle properties microphysics
  - 48 h forecasts (2/day)
  - Uncoupled since Jan. 24, 2018
  - Coupled since Jun. 28, 2018
  - Decommissioned in Feb. 2022
  - Re-instated in 2024!



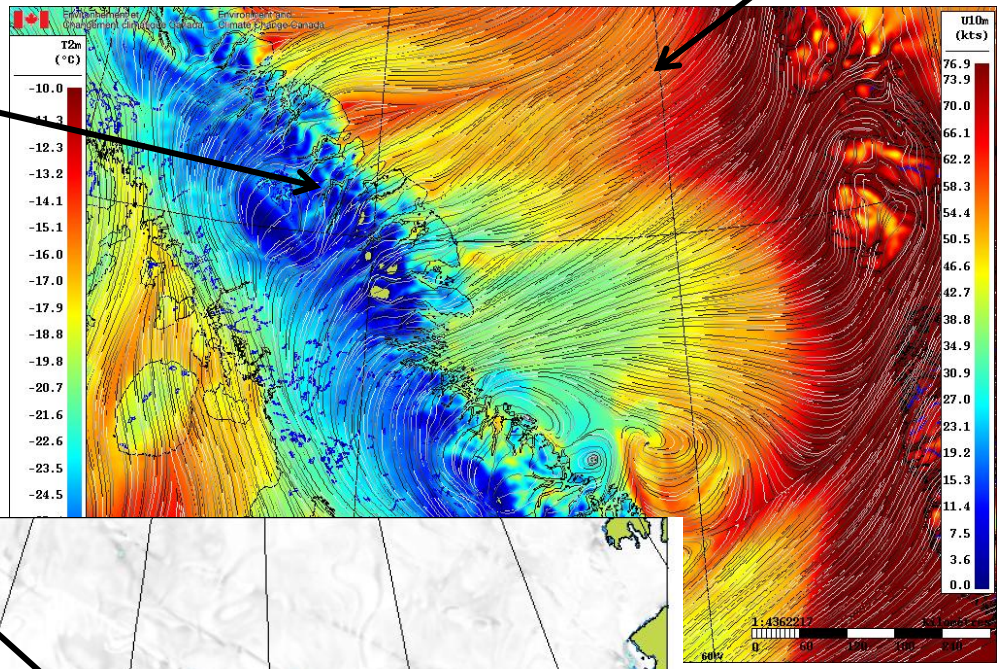
Casati et al. (Atm-Ocean, 2023)

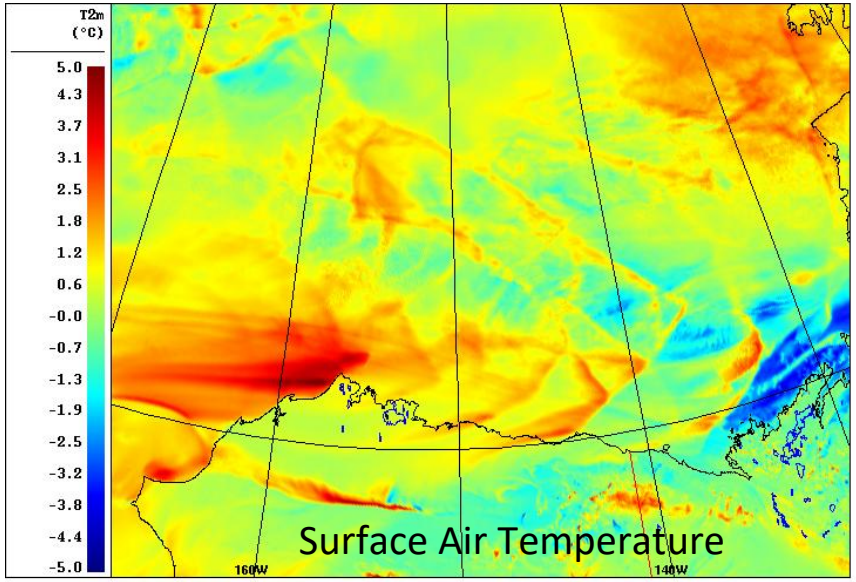
Impact of small-scale coupled atmosphere-ice-ocean interactions in the Canadian Arctic Prediction System (CAPS)

- Orographic features better represented
  - Flow through fjords
  - Potential impact on local ice drift
- Imprint of small-scale features on surface fluxes
  - Boundary layer interactions in marginal ice zone
  - Coastal polynyas and leads in sea ice

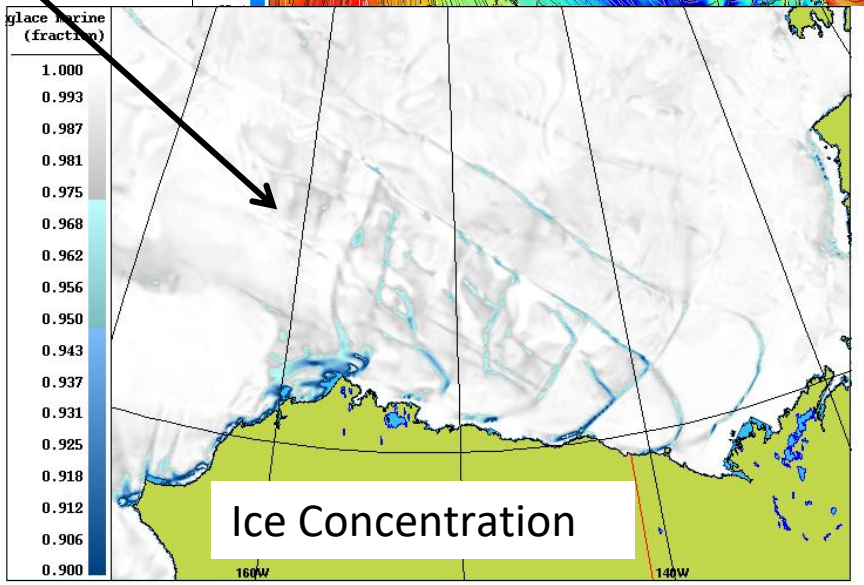


Forecast for 2017-01-01





Surface Air Temperature



Ice Concentration

Effects of coupling on near-surface temperatures

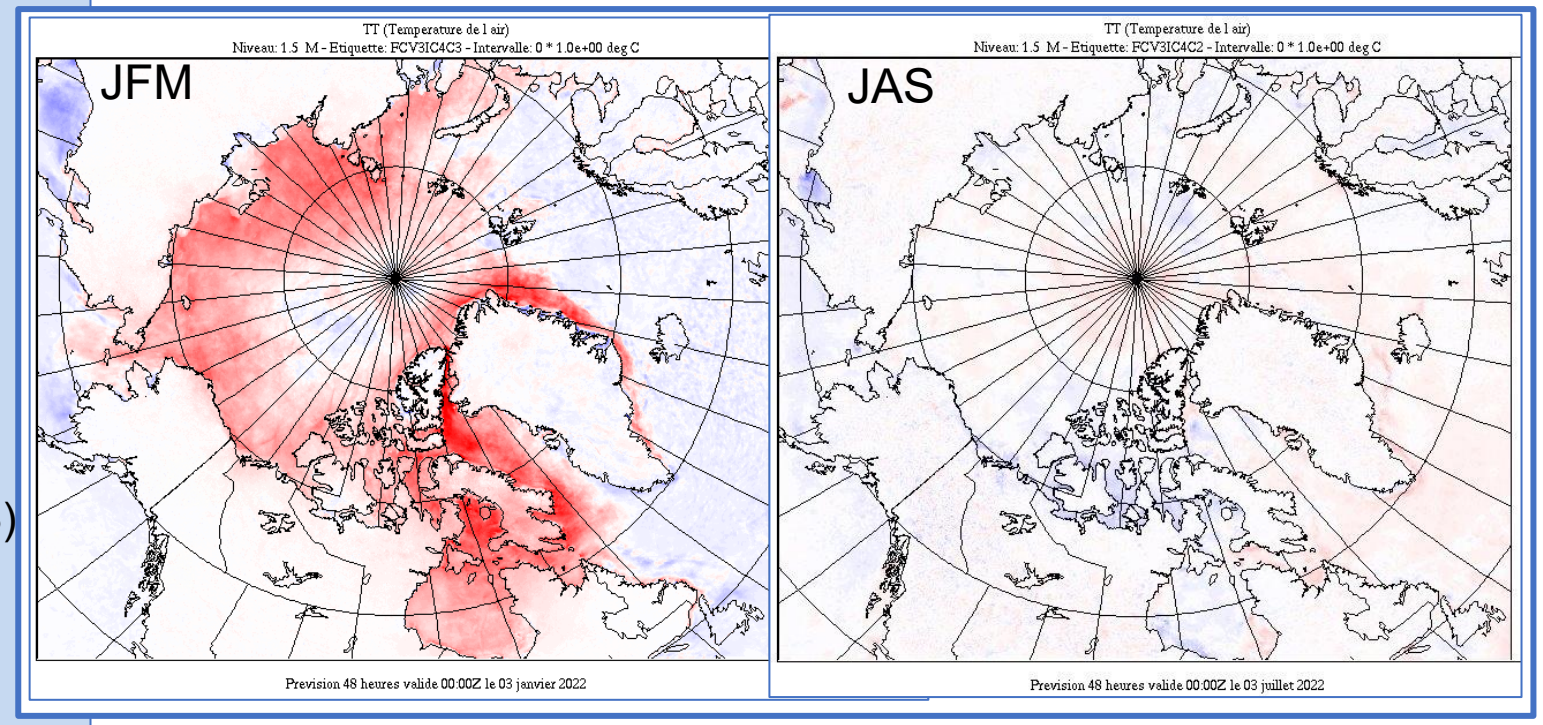
Over Sea ice
- Large-scale wintertime warming (2-5°C)
- No significant differences in summer

Over Ocean
- Cooling in fall-winter-spring

Over land
- No clear signal except coastal areas

Explained by:
- Leads under-represented in ice analysis (RIPS)
  - Initial conditions
- Opening of leads in coupled forecasts
  - vs. persistence in uncoupled
- Large-scale differences in surface turbulent fluxes
- Differences snow-on-ice
- Heat fluxes through the ice (ITD...)

ΔT2m : Coupled – Uncoupled
Average differences after 48h forecast

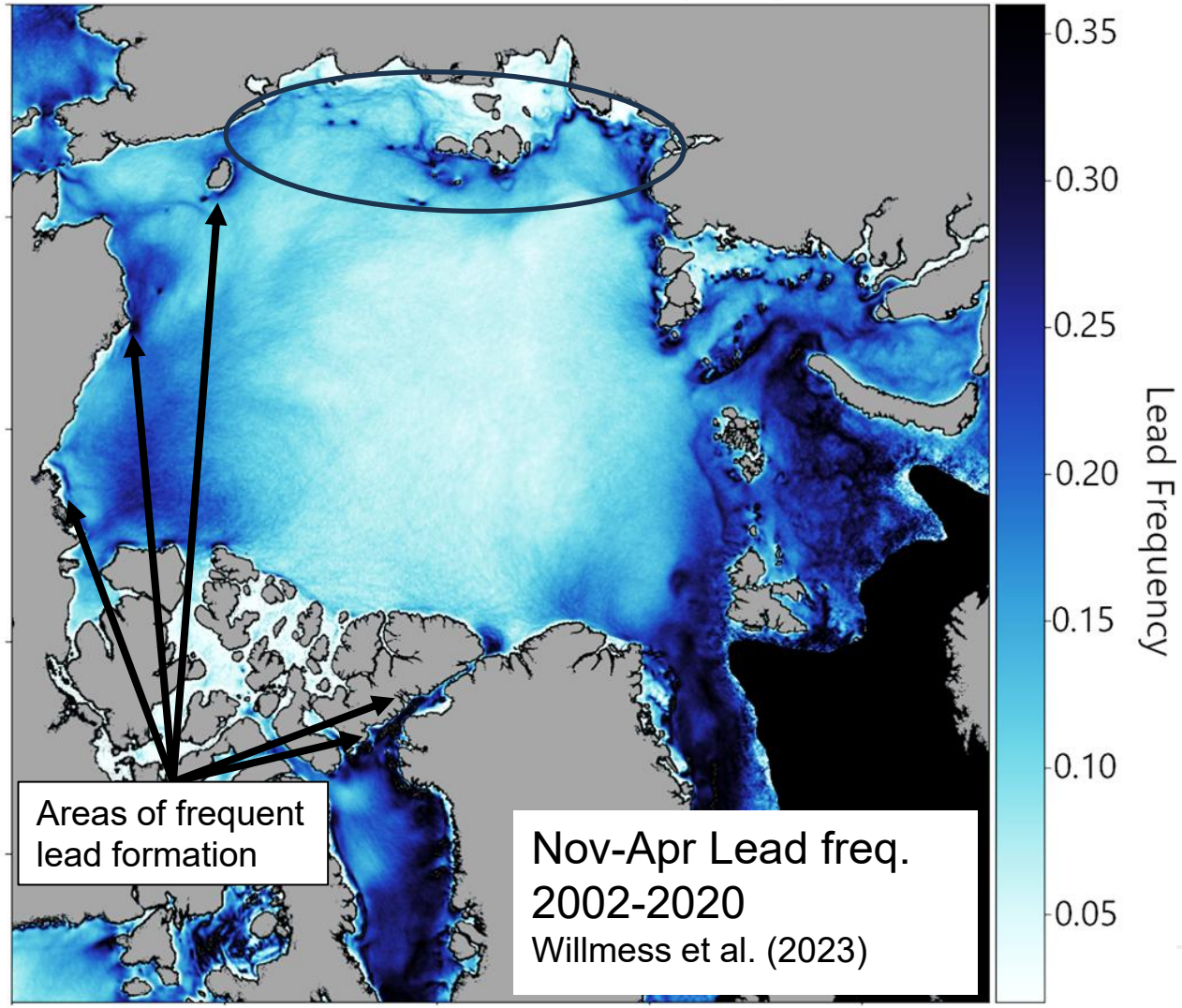


Changes in Turbulent Heat Fluxes

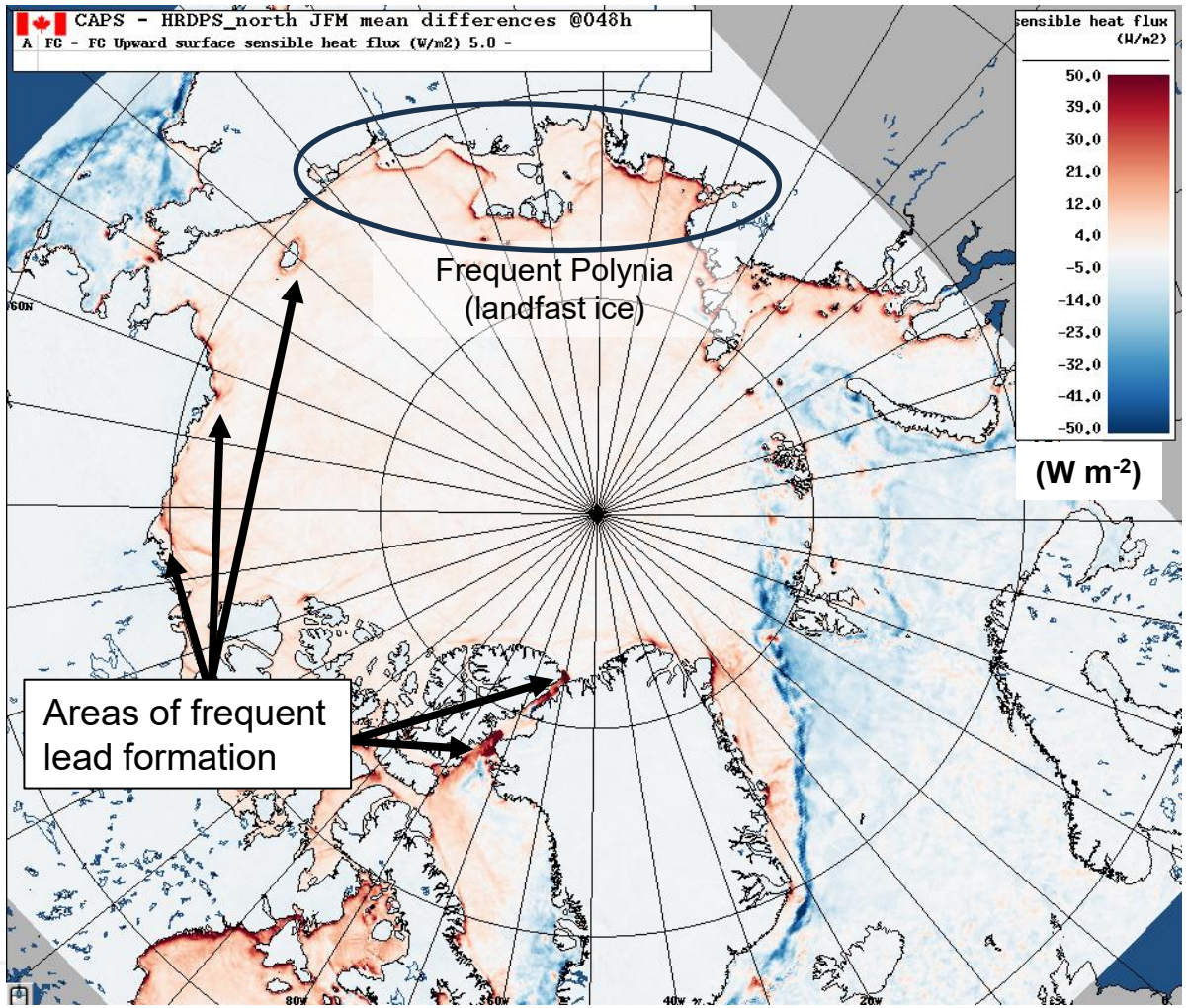
Winter (JFM) turbulent heat fluxes differences (at 48h)

CAPS: Coupled – Uncoupled

(b) ArcLeads mean lead frequency

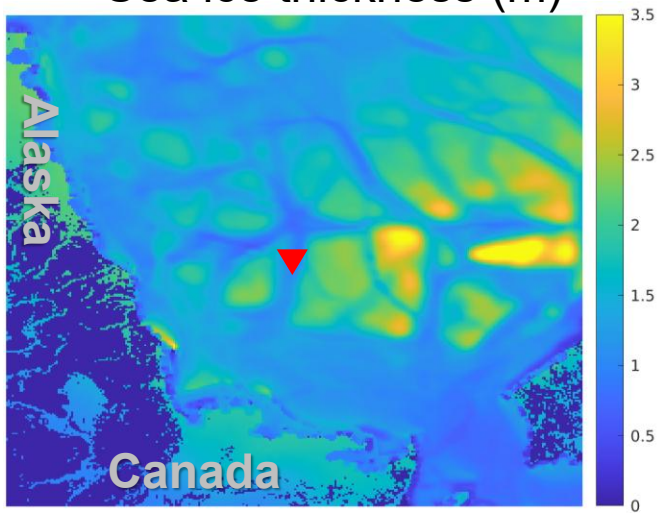


Sensible heat flux differences

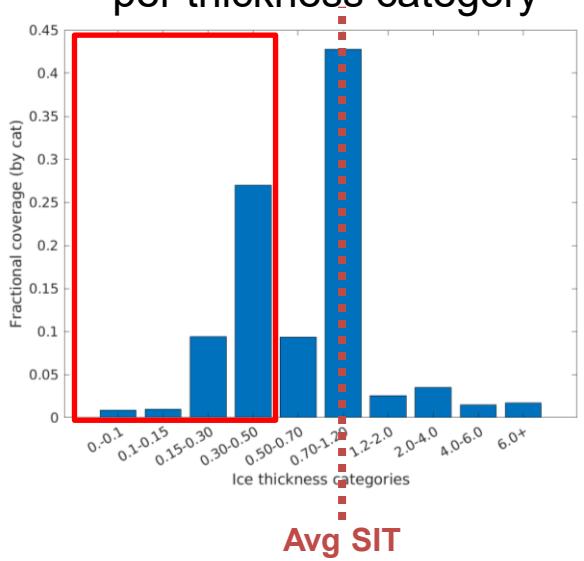


Heat flux through the ice – Case study 2022-01-01

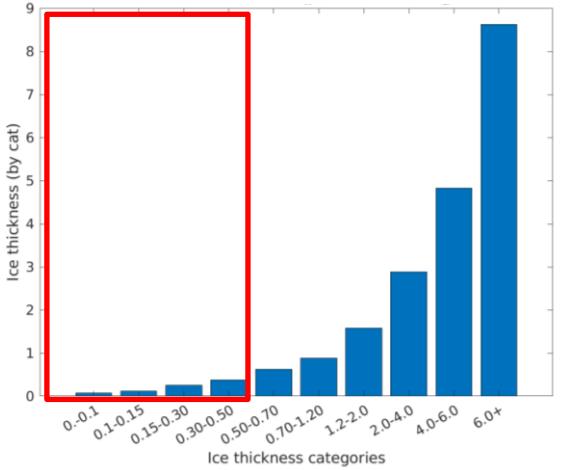
Sea ice thickness (m)



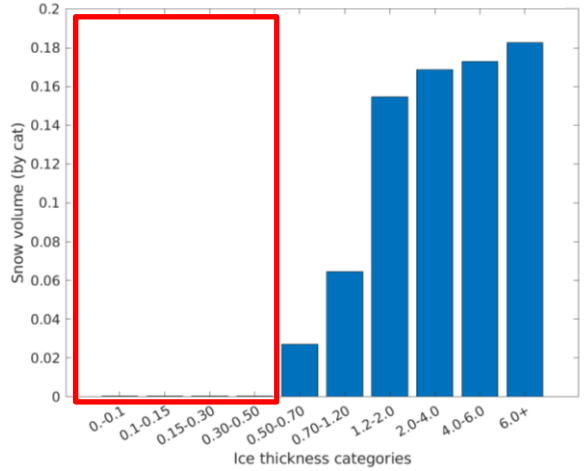
Sea ice cover
per thickness category



Ice thickness by cat.

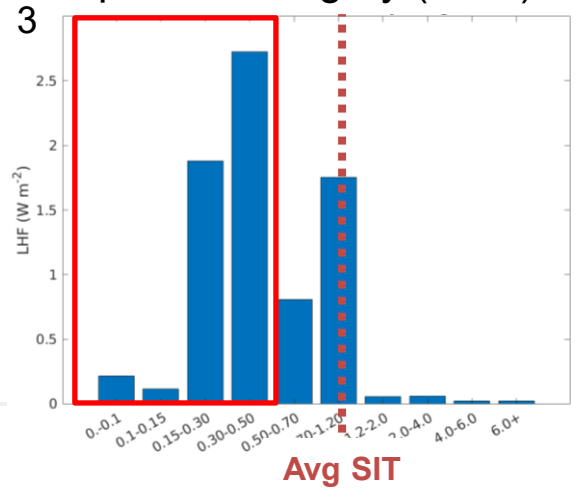


Snow thickness by cat.

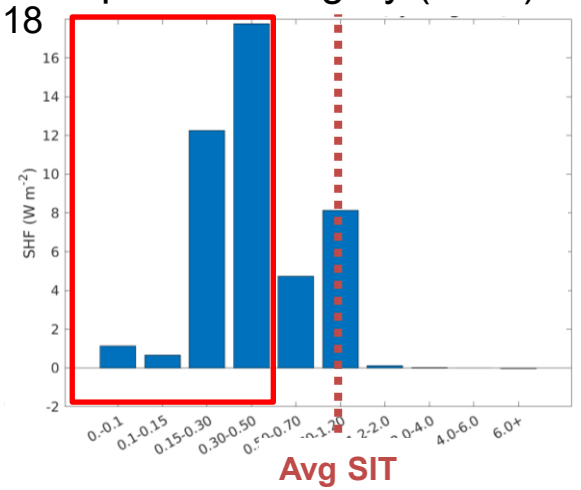


Time series extracted at: ▼
Sea ice cover 99%
Sea ice thickness 0.92m

Normalized Latent HF
per ice category (Wm^2)



Normalized Sensible HF
per ice category (Wm^2)

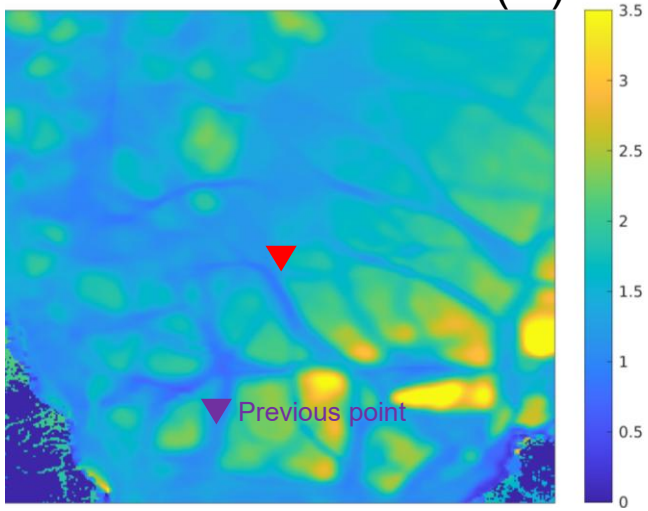


SHF aggregated
Coupled = 45 Wm^{-2}
Uncoupled= 9.8 Wm^{-2}

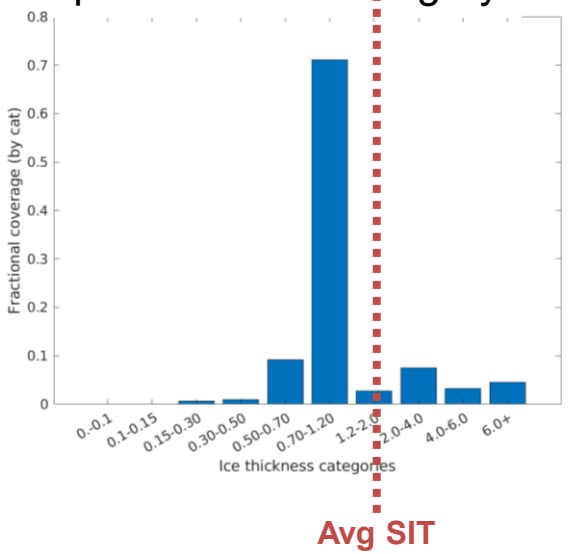
Paquin et al. (in prep)

Heat flux through the ice – Case study 2022-01-01

Sea ice thickness (m)

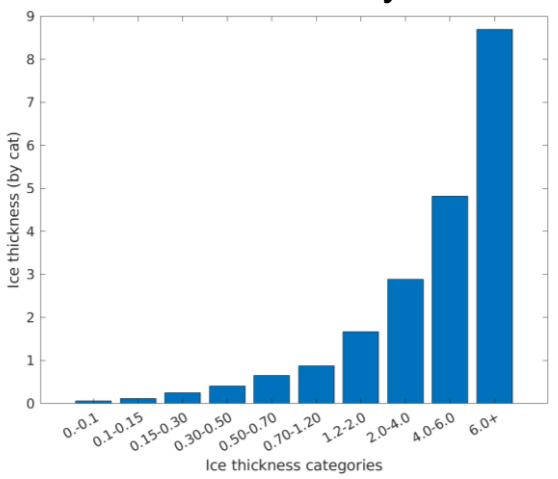


Sea ice cover
per thickness category

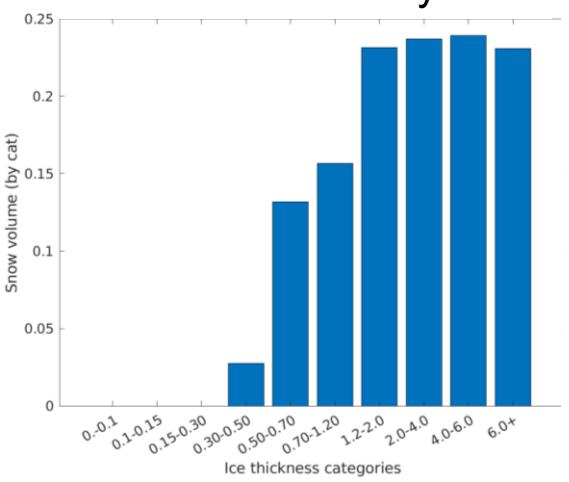


Avg SIT

Ice thickness by cat.

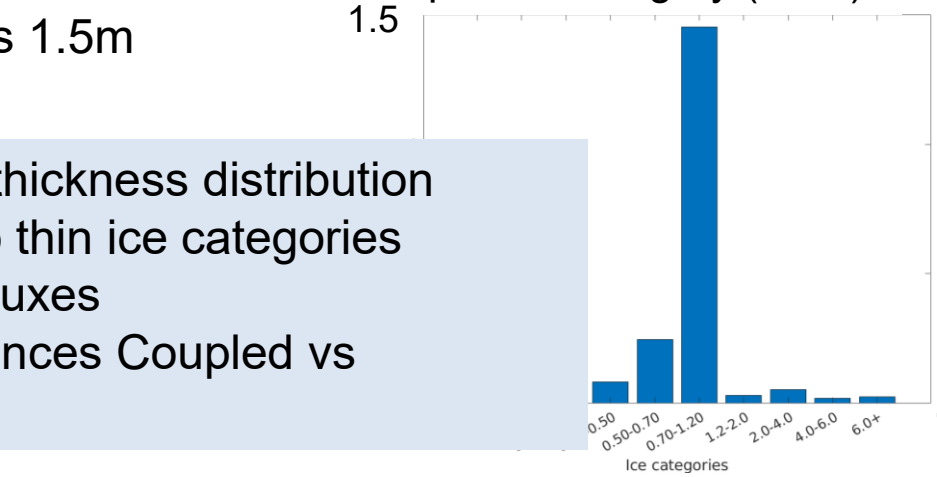


Snow thickness by cat.

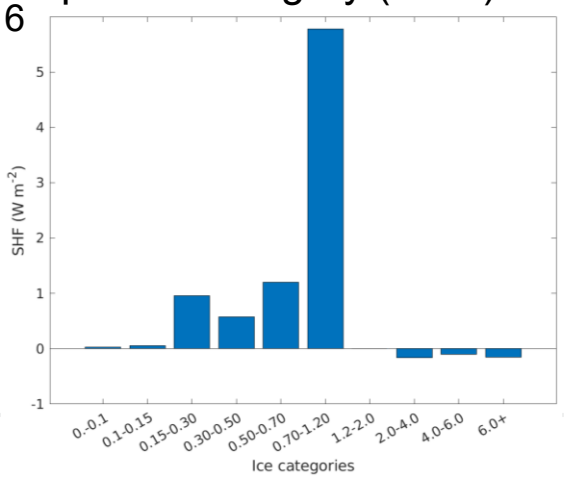


Time series extracted at:
Sea ice cover 99%
Sea ice thickness 1.5m

Normalized Latent HF
per ice category (Wm^2)



Normalized Sensible HF
per ice category (Wm^2)



- More uniform thickness distribution
  - Almost no thin ice categories
- Smaller heat fluxes
- Smaller differences Coupled vs Uncoupled

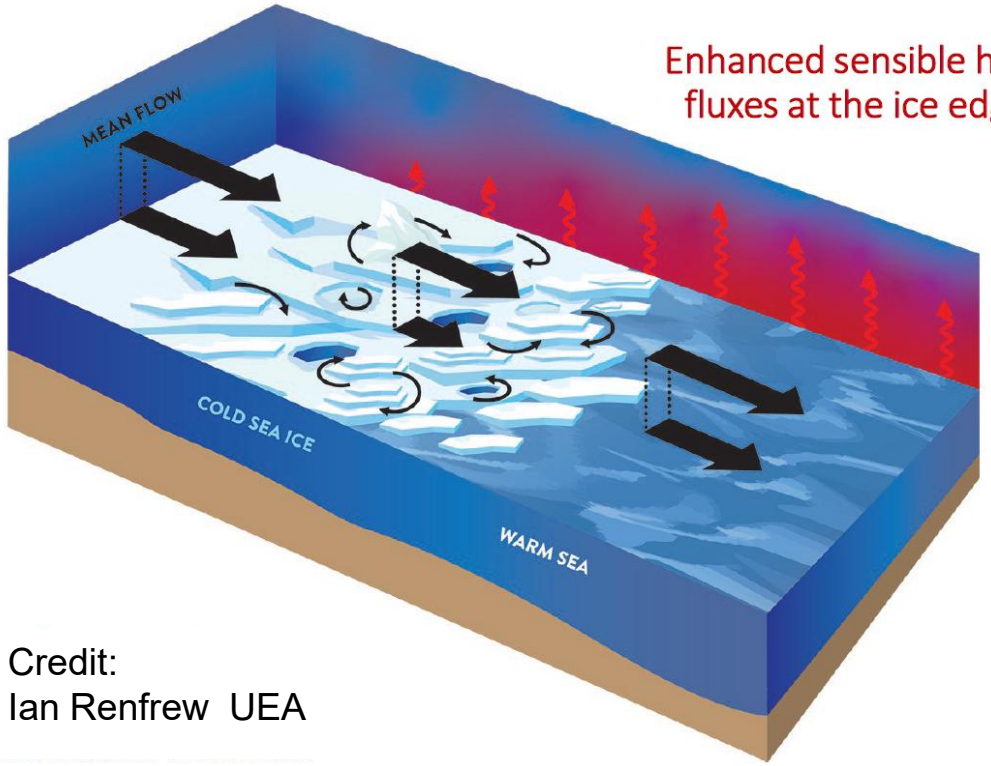
SHF aggregated
Coupled = 8.2 Wm^2
Uncoupled= 2.3 Wm^2

Paquin et al. (in prep)

Ongoing Research

Improving physical processes in CAPS

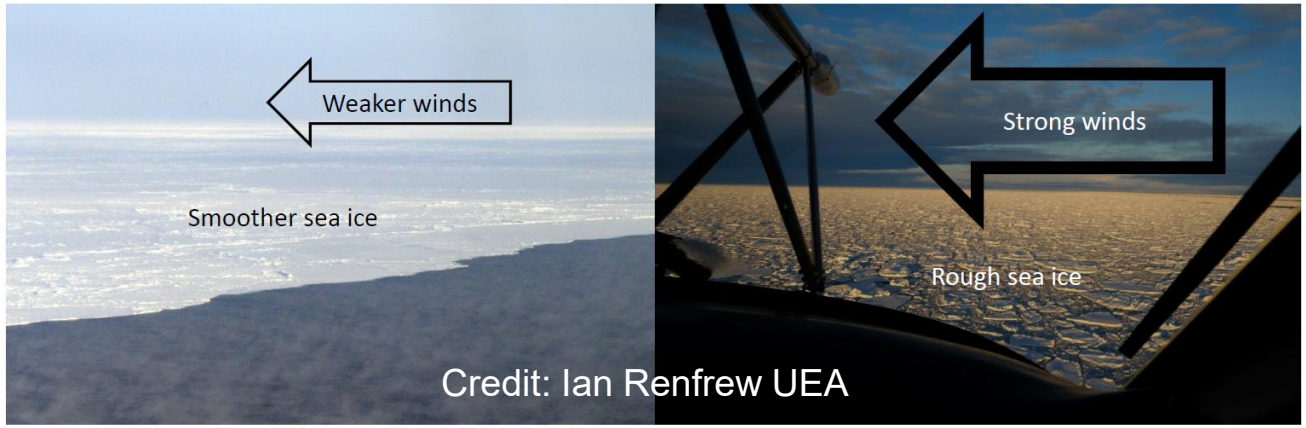
- **Winter clouds & radiative properties**
  - **Microphysics**
  - **Correct warming drift of surface air temperatures**
- **Coupled processes in boundary layers**
  - **Representation of marginal ice zone on ABL**
  - **air-ocean interactions in ice-infested areas**
  - **High-frequency coupling on rapid changes in sfc conditions**
  - **Special observing periods (IGP, ACCACIA, SvalMIZ, etc.)**
- **Improvements on sea ice representations**
  - **Rheology, landfast ice, form drag, ice thickness insertion thermodynamics (mushy layer)**
- **Add wave-ocean & wave-ice interactions**
  - **Vertical mixing & heat transfer**
  - **Wave attenuation in MIZ**
  - **ice breaking due to wave activity**
- **New IRIS coupler**
  - **Efficiency & flexibility**



Credit:
Ian Renfrew UEA

ACCACIA

IGP



Iceland-Greenland Seas Observing Period (Feb - Mar 2018)

- **Collocated A-I-O observations**
- **Meteorologically active period (Cold air outbreaks; CAO)**

Develop flexible modeling framework

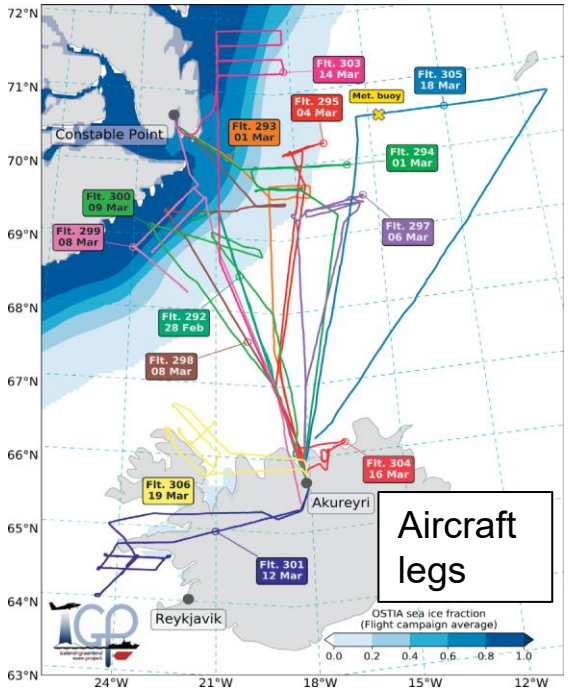
- Continuous atmospheric runs (balanced BL)
- Use spectral nudging to control the synoptic scales in the free atmosphere
  - Optimizes comparison with obs (timing)
- Forecast & sensitivity experiments

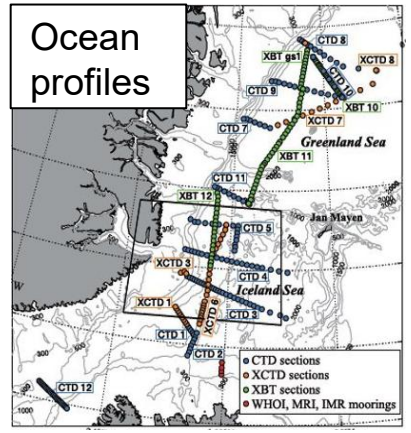
Evaluation

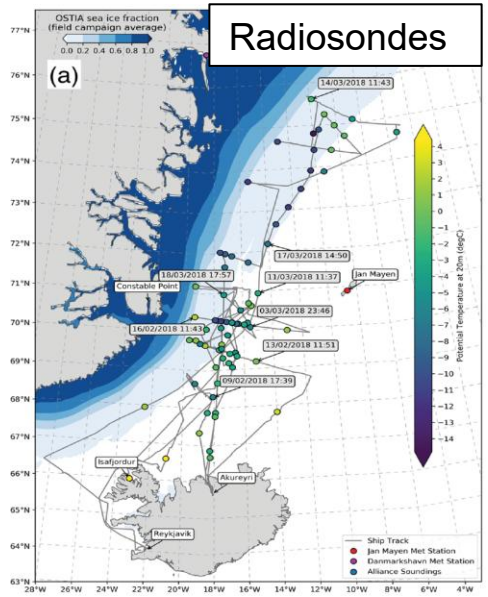
- Predictability of **CAO**
- Impact of resolution on **CAO**
- Impact of **CAO** on sea ice / ocean surface layer
- Representation of sea ice on surface fluxes, atmospheric boundary layer (coupled & uncoupled)
- **Initialization shock** on forecast errors
- **Forecast error growth** (persistent surface fields vs. coupled)
- **Innovations** (form drag, ABL parameters, microphysics, etc.)

Apply methodology to other campaigns:

- ACCACIA, MOSAiC, SvalMIZ, THINICE, others







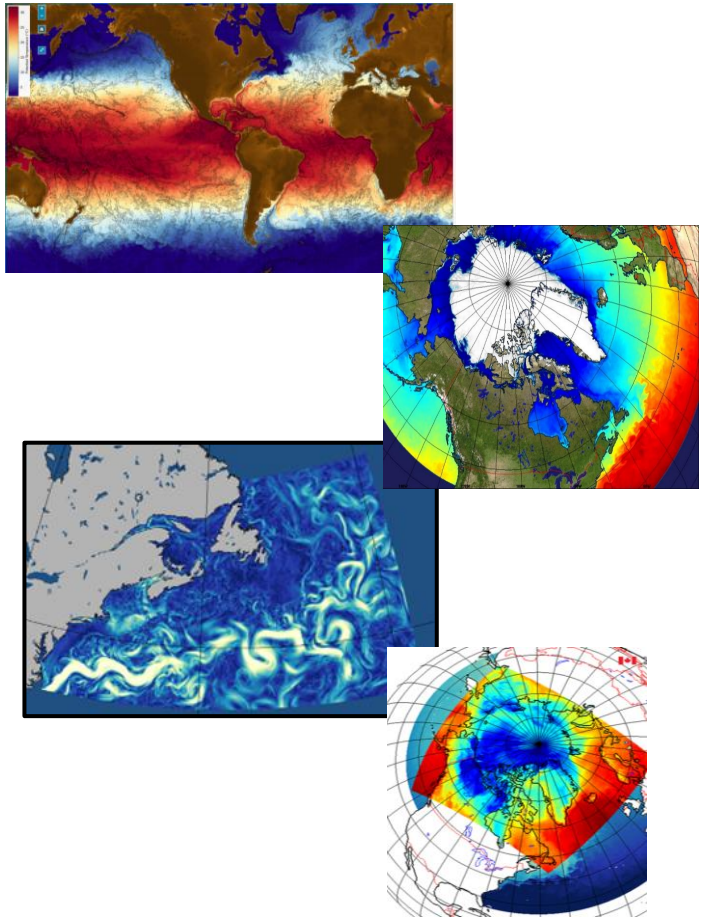
Renfrew, I. A., et al. 2019: The Iceland Greenland Seas Project. *BAMS* **100**, 1795–1817, https://doi.org/10.1175/BAMS-D-18-0217.1.

Historical reconstructions (reanalysis)

- Global and regional systems required for assessing extreme events, climate impacts and machine learning!
- Global reanalysis needed for initializing Monthly and Seasonal systems

Projects

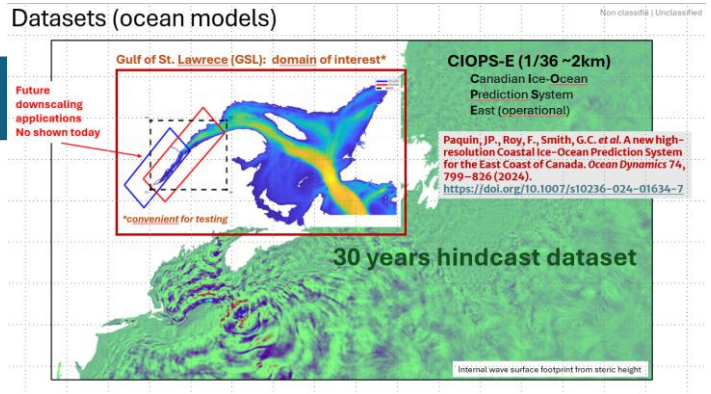
- **GIOPS Reanalysis (1993-2022):**
  - Uses IC5 SAM2v2 configuration (iORCA025-L75)
  - Initialized from EN4, assimilates CORA T/S profiles, CMC SST and various nadir altimeters
  - Prototype with no sea ice assimilation produced. Results broadly consistent with GLORYS4v2 and GLORYS12.
  - Next steps:
    - Production of a separate sea ice reanalysis underway.
    - Working on new method to assimilate pseudo-Argo profiles (pre-2005) to correct water mass biases.
- **1/12th Three-Oceans multi-decadal hindcast** (1958-2024)
  - Assess longer-term variability and trends in water masses, circulation and sea ice around Canada
- **CIOPS Retrospective Simulation** (1993-2022)
  - Regional downscaling of GLORYS12 using spectral nudging offshore
  - Analysis of variability, extremes and trends underway
- **CAPS/RIOPS "reanalysis" (PROPOSED):**
  - RIOPS reanalysis following approach used for GIOPS
  - Include additional Canadian coastal observations for 3 oceans (Pac, Arc, Atl)
  - Use CAPS coupled configuration with spectral nudging in the atmosphere toward ERA5.

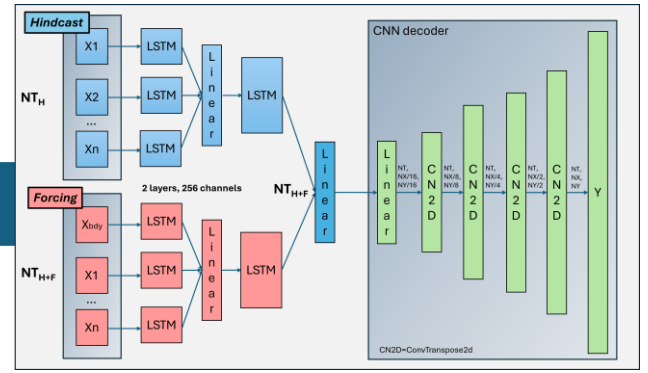


Ongoing efforts in ocean AI/ML at ECCC

Areas of interest

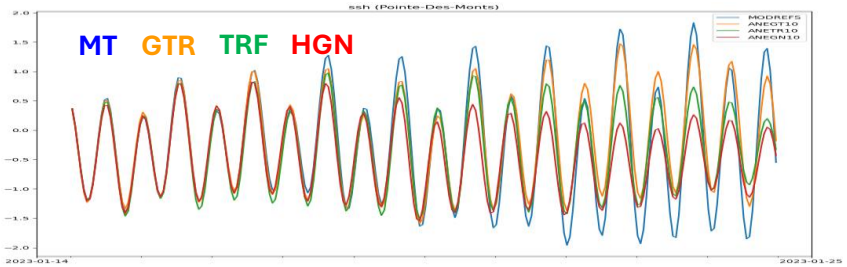
- **Global Emulators**:
  - Use of GloNet or Anemoi, spectral nudging in GIOPS, participation in OceanBench
  - Working on GIOPS reanalysis as part of CMEMS GREP (CMOS presentation)
  - Use of emulator as part of assimilation system and for ensembles
- **Regional Emulators:**
  - Working on emulator for RIOPS/CAPS using Anemoi (GNN)
    - Key challenge: capturing detailed ice edge and including tidal variability
- **Coastal Emulators and downscaling**:
  - Emulator for CIOPS using LSTM and Anemoi
  - Downscaling to GSL500 and SS500





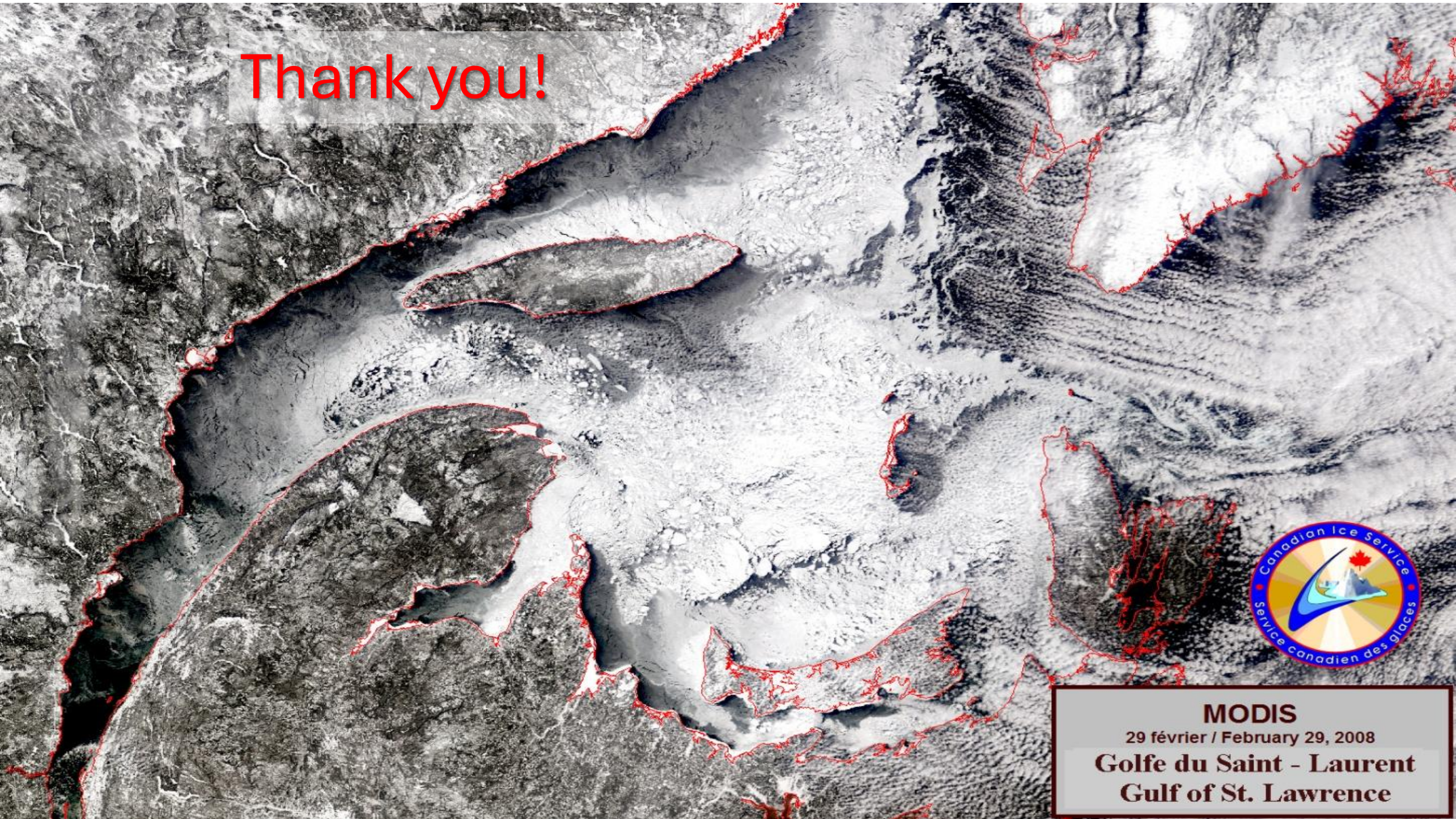
Overarching issues

- Need for high-quality training datasets
- How to exploit ML for new applications (data assimilation, compression, …)
- New physically-based evaluation approaches to ensure quality of forecasts and products
- How to accommodate need for integrated platforms (digital twins) and diversity of ML applications that are expected to develop over next few years



F. Roy, G. Smith, F. Dupont, C. Hebert-Pinard, R. Islam, Y. Martinez, Y. Liu

Thank you!


Canadian Ice Service
Service canadien des glaces
MODIS
29 février / February 29, 2008
Golfe du Saint - Laurent
Gulf of St. Lawrence

CAPS updates & improvements
Atmospheric model (GEM) – Integrated impacts vs OPS

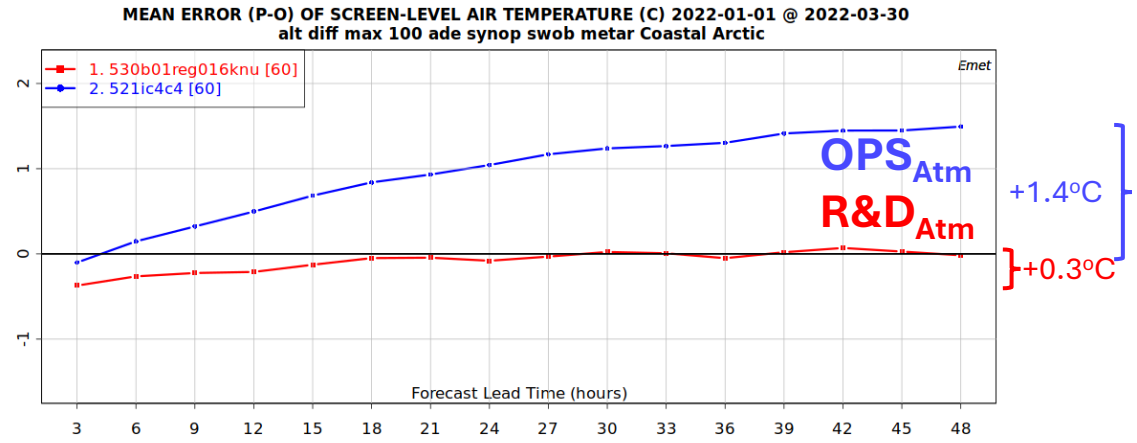
Bias

Improvement / Degradation		Fall 20211015 / 20211230			Winter 20220101 / 20220330			Spring 20220401 / 20220630			Summer 20220701 / 20220930		
		00z	12z	All	00z	12z	All	00z	12z	All	00z	12z	All
Coastal Arctic	TD	0.27	0.33	0.31	0.74	0.72	0.73	0.14	0.11	0.12	0.035	0.026	0.025
	TT	-0.06	-0.066	-0.049	0.81	0.83	0.86	0.054	0.074	0.092	0.019	0.02	0.012
Coastal North Atlantic	TD	0.037	0.019	0.029	0.041	0.059	0.014	0.057	0.05	0.042	-0.005	0.0074	0.00095
	TT	0.07	0.052	0.082	-0.058	-0.052	-0.057	0.0022	-0.014	-0.0053	-0.04	-0.015	0.016
Coastal North Pacific	TD	0.099	0.17	0.11	0.13	0.15	0.15	-0.03	-0.074	-0.039	0.0095	-0.028	-0.001
	TT	-0.052	0.016	0.0088	0.027	0.07	0.028	0.029	0.065	0.048	-0.054	-0.05	-0.0024
Inland Arctic	TD	0.058	0.091	0.083	0.12	0.1	0.14	-0.02	-0.028	-0.025	-0.0057	0.0021	0.00011
	TT	-0.13	-0.056	-0.1	-0.27	-0.25	-0.28	-0.03	-0.029	-0.03	0.013	0.013	0.021

RMSE

rmse 530b01reg016knu / 521ic4c4		Fall 20211015 / 20211230			Winter 20220101 / 20220330			Spring 20220401 / 20220630			Summer 20220701 / 20220930		
		00z	12z	All	00z	12z	All	00z	12z	All	00z	12z	All
Coastal Arctic	TD	9.87%	9.25%	9.56%	17.33%	16.78%	17.06%	8.16%	8.21%	8.20%	5.41%	4.41%	4.94%
	TT	6.71%	6.67%	6.62%	16.06%	15.90%	15.96%	6.07%	7.25%	6.69%	2.98%	3.92%	3.35%
Coastal North Atlantic	TD	6.20%	5.80%	6.01%	4.23%	4.83%	4.54%	4.05%	4.00%	3.96%	3.69%	4.29%	3.97%
	TT	3.99%	4.39%	4.22%	1.31%	2.34%	1.95%	4.50%	4.18%	4.76%	5.26%	5.51%	5.38%
Coastal North Pacific	TD	6.77%	8.31%	7.54%	8.81%	9.38%	9.10%	3.89%	2.91%	3.36%	3.49%	3.57%	3.69%
	TT	0.81%	4.12%	3.06%	8.05%	8.56%	8.33%	3.66%	2.79%	3.35%	1.37%	2.13%	1.84%
Inland Arctic	TD	10.42%	10.25%	10.33%	10.06%	10.90%	10.46%	2.96%	3.36%	3.25%	1.77%	1.83%	1.86%
	TT	7.91%	8.12%	8.02%	7.91%	8.14%	8.07%	2.83%	2.67%	2.83%	2.42%	2.36%	2.44%

Winter (JFM) air temperature bias vs coastal stations



Summary (atm-only)

- Drift controlled over Coastal Arctic
- RMSE improved for all seasons
- Improves mostly coldest temperatures
- Compensating errors (*Cold bias over land*)

Atmospheric Spectral Nudging

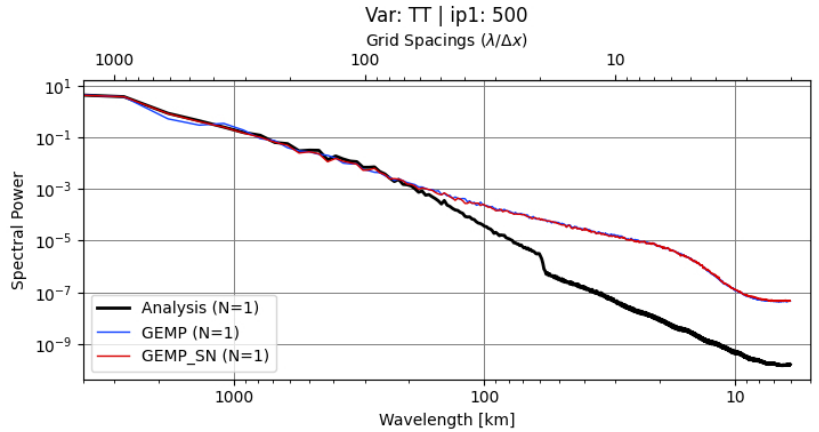
Spectral nudging (Von Storch[1] ; Husain[2])

- correct GEM synoptic scales towards reliable source (ERA5)
- *do not interfere with GEM small scales*
- applied to prognostic variables (T_v, U, V,)

- Horizontally
  - correct scales > 800 km (λ_{LS})
  - no nudging at scales < 500km (λ_{SS})
  - decreasing nudging strength between λ_{LS} & λ_{SS}

- Vertically
  - nudging applied in the free atmosphere
  - no nudging near surface or close to model lid
  - Control by 4 parameters

Power spectra: 500 hPa Temperature



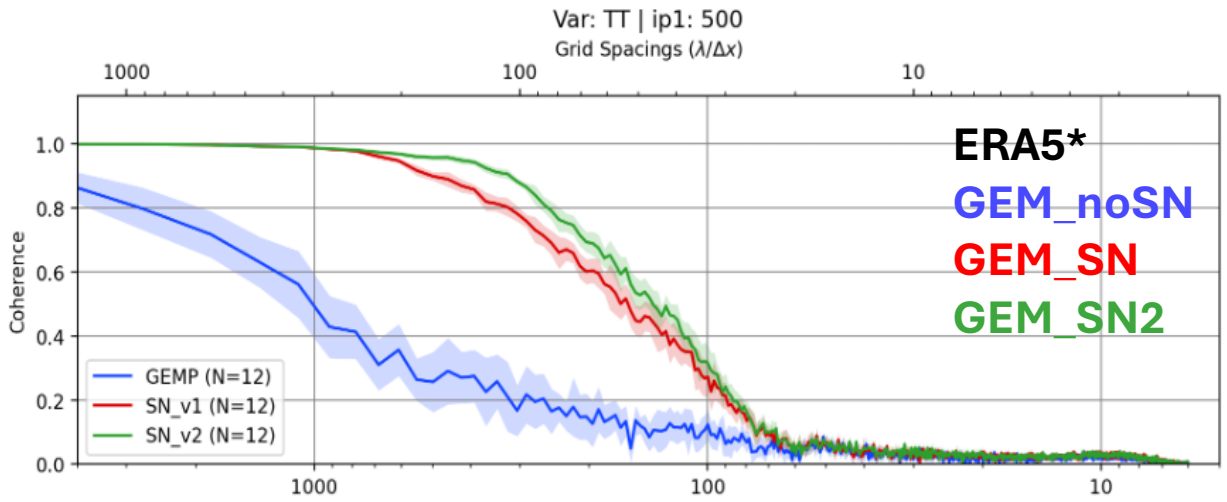
- ERA5 (interpolated on CAPS 3-km grid)
  - Effective resolution about ~200 km
- GEM has more energy in smaller scales
  - Effective resolution ~20-30km (6-10Δx)

[1]Von Storch et al. (2000) 10.1175/1520-0493(2000)128<3664:ASNTFD>2.0.CO;2
[2]Husain et al. (2025) doi.org/10.1175/WAF-D-24-0139.1

Canada

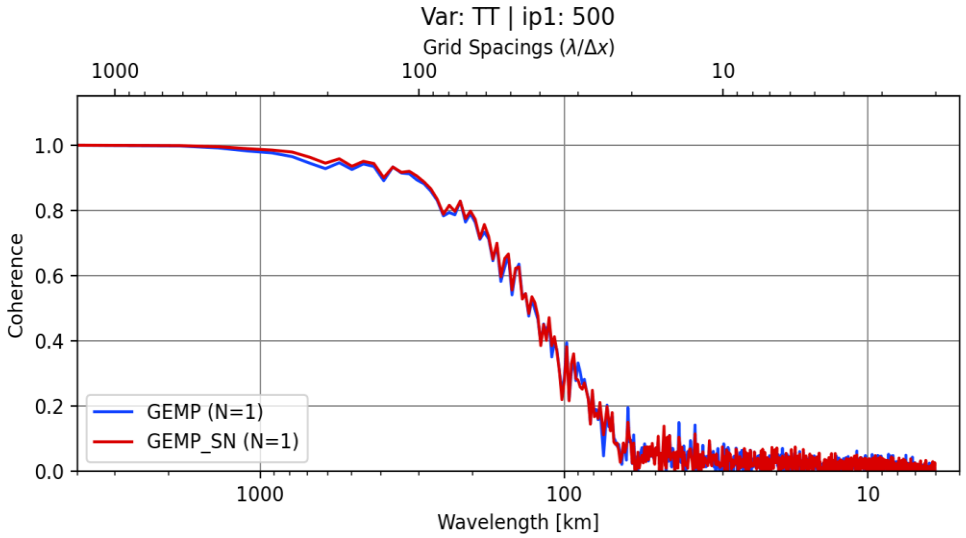
Atmospheric Spectral Nudging

Average coherence : 500 hPa Temperature



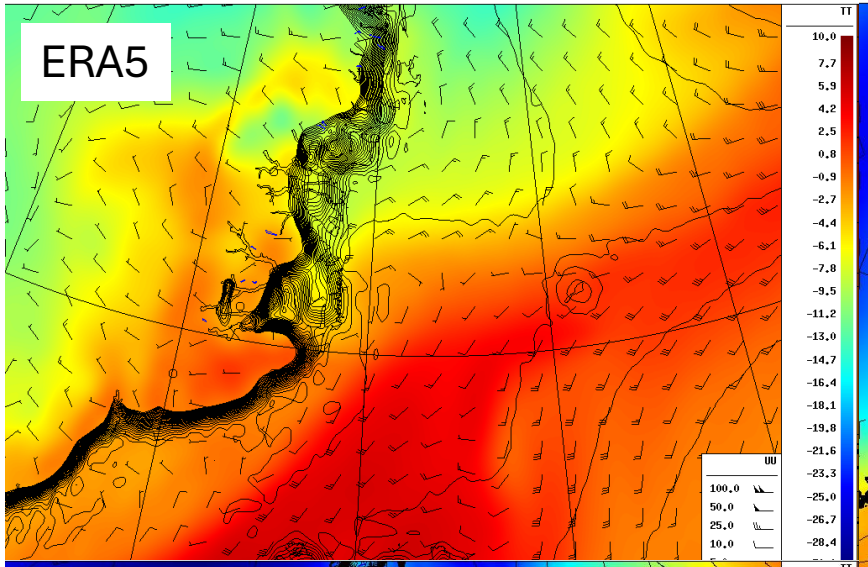
- Averaged coherence w.r.t. ERA5 (over 15 days runs)
- No SN : lower coherence across scales
- With SN : Coherence above λ_{LS} =800km is ~1.
- v2 nudges smaller scales (λ_{LS} =500km; λ_{SS} =250km)

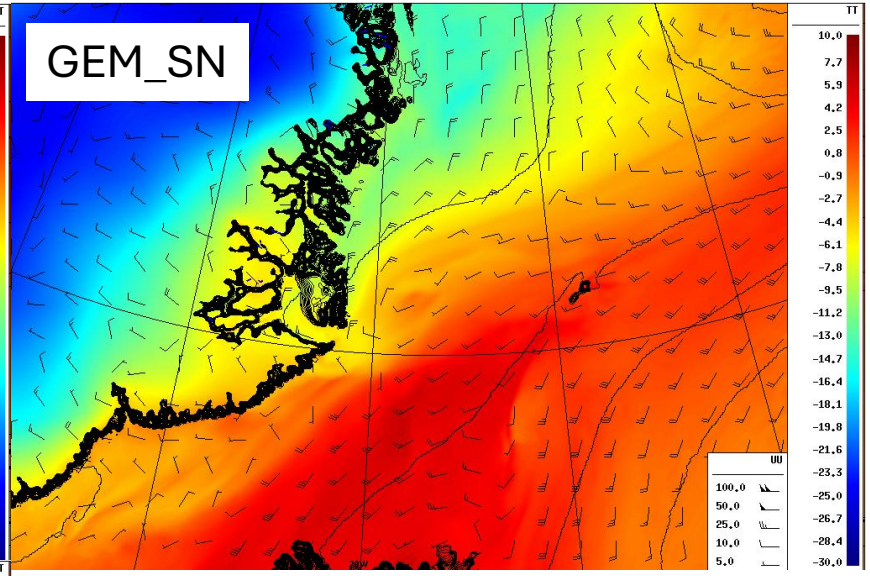
Coherence every 24h : 500 hPa Temperature

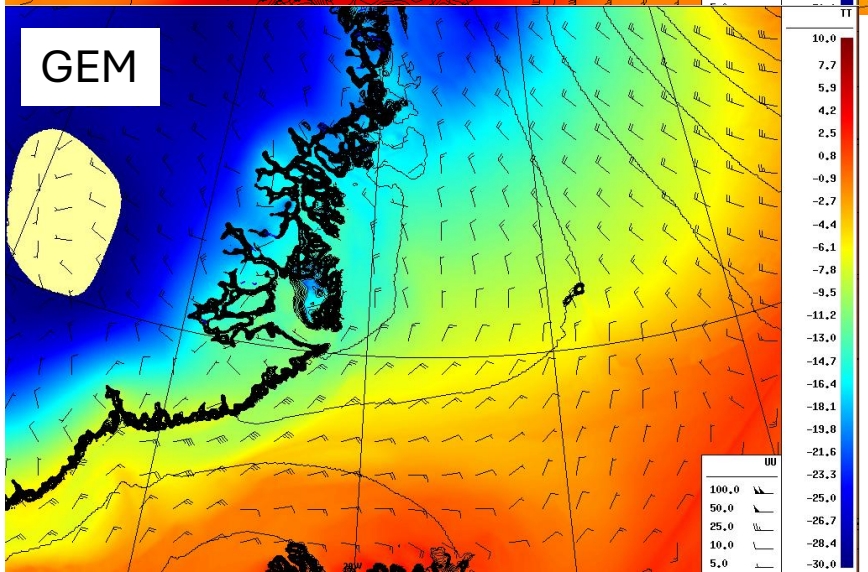


- GEM coherence decrease rapidly after initialization
- GEM_SN retains coherence with ERA5

Modeling framework for evaluating CAPS during observation campaigns
Iceland-Greenland Seas Project







Feb 28th 2018 (00Z)
1000mb TT
Surface pressure
Winds

- GEM_SN : closer to ERA5 for near-surface variables (not directly nudged)
- GEM better representation of topography
- Small scale circulation (topographic control) near Constable Point

Summary
- Spectral nudging is promising
- Start working next on comparison with observations