Environment and Climate Change Canada / Environnement et Changement climatique Canada

Towards Strongly Coupled Data Assimilation at Environment Canada

Mark Buehner, Sergey Skachko, Alain Caya, Alex Komarov
Meteorological Research Division

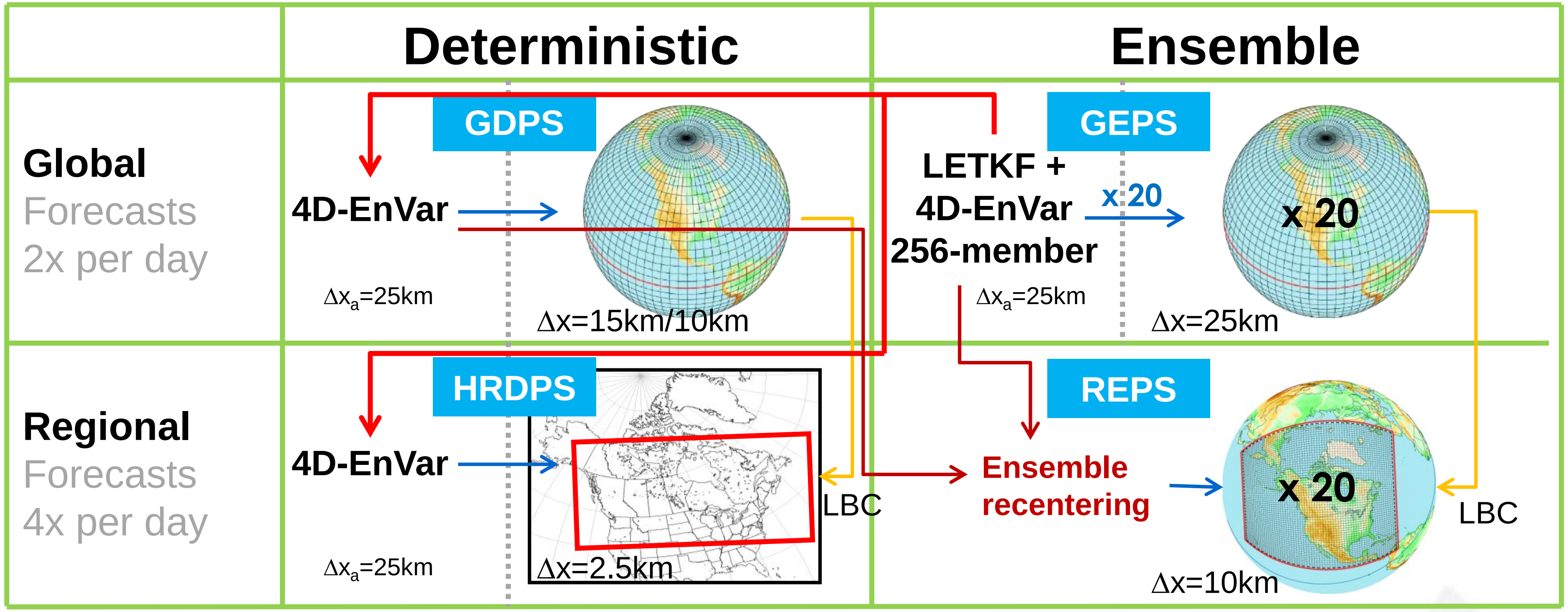
GHRSST25 International SST Users' Symposium
June 2024

Canada

Contents

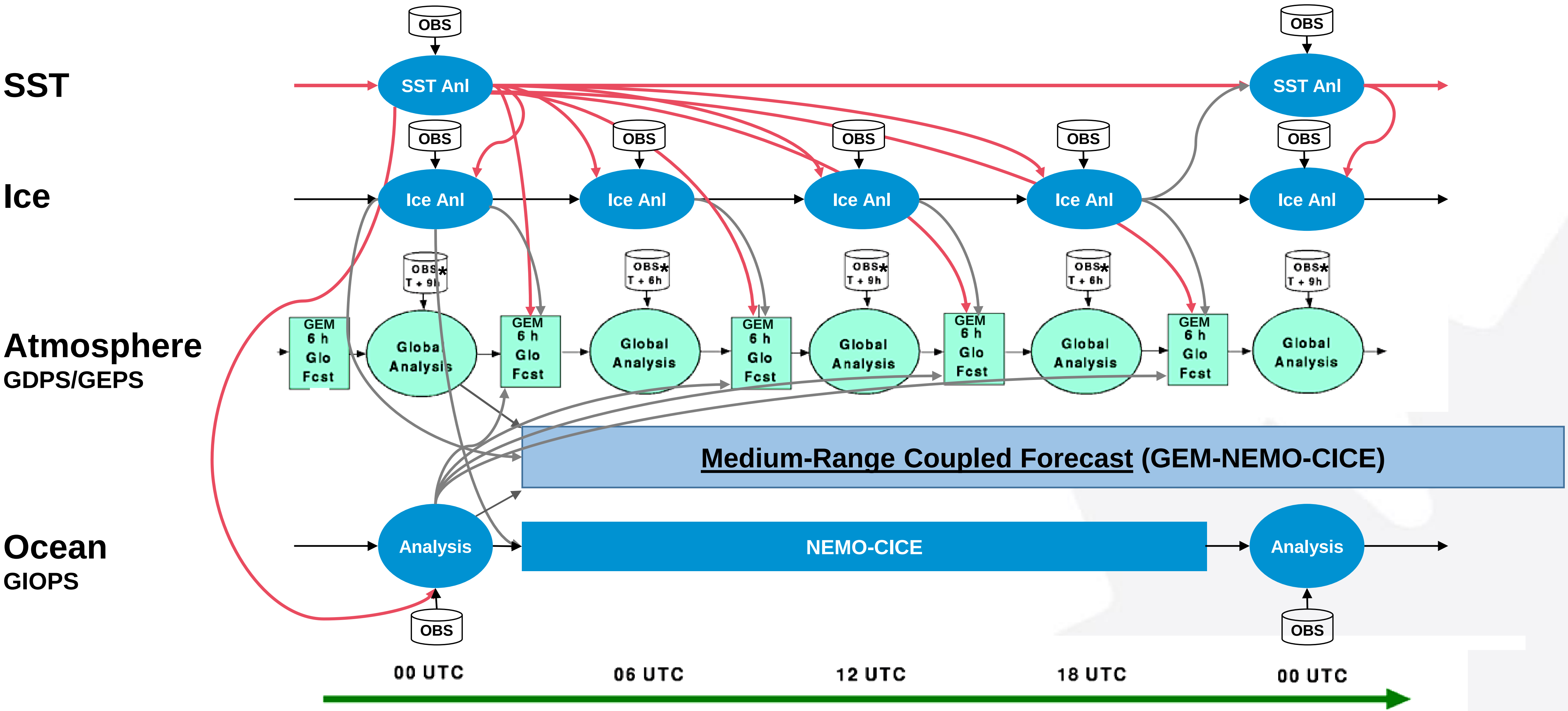
- Overview of current NWP systems and role of SST/sea ice analyses
- Why consider strongly coupled data assimilation?
- Increasing use of MIDAS for Earth system data assimilation
  - By first using the same software and assimilation algorithm for each Earth system component, this facilitates gradual transition to coupled assimilation
- Role of SST analysis in current NWP assimilation system
- The ECCC sea ice analysis (in MIDAS): concentration, type, thickness
- New SST analysis implemented in MIDAS as a step towards full 3D ocean assimilation with LETKF
- Incremental next steps towards strongly coupled assimilation

ECCC operational NWP systems



- Global medium-range deterministic and ensemble NWP forecasts are **coupled to ocean-ice model**, initialized with **uncoupled data assimilation systems**
- Global ensemble system (GEPS) provides ensemble covariances to all other systems
- Developed “in-house” SST and sea-ice analysis systems that provide their analyses to all other systems

Interaction of uncoupled global assimilation systems



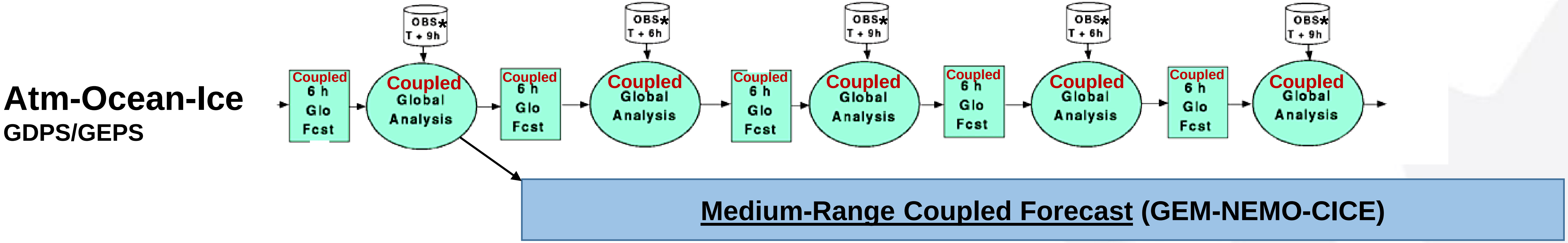
Interaction of uncoupled global assimilation systems

- Many connections between the “uncoupled” assimilation systems
- SST analysis is used for:
  - Sea-ice obs QC to remove spurious non-zero ice concentration retrievals
  - Remove ice in simple persistence model for cycling in sea ice assimilation system
  - Lower boundary condition for background atmospheric forecasts in NWP systems
  - Assimilated by 3D ocean assimilation
- Sea-ice analysis is used for:
  - Deciding where to assimilate satellite SST obs vs. artificial obs set to the freezing point
  - Lower boundary condition over lakes for background atmospheric forecasts in NWP systems
  - Partially specify ice concentration in ocean-ice model forecasts
- Ocean-ice state from ocean-ice prediction system used for:
  - Lower boundary condition of ice concentration/thickness and snow depth on ice over ocean for background atmospheric forecasts in NWP systems

Towards coupled data assimilation

Possible future coupled global assimilation system

- Potential advantages of fully coupled data assimilation system:
  - Reduce the number of systems and more easily include links between components
  - Observations of one component can provide corrections to another through coupled ensemble covariances in LETKF and 4D-EnVar → consistency near component interfaces
  - Observations directly related to multiple components can be more optimally utilized (e.g. surface-sensitive radiances)



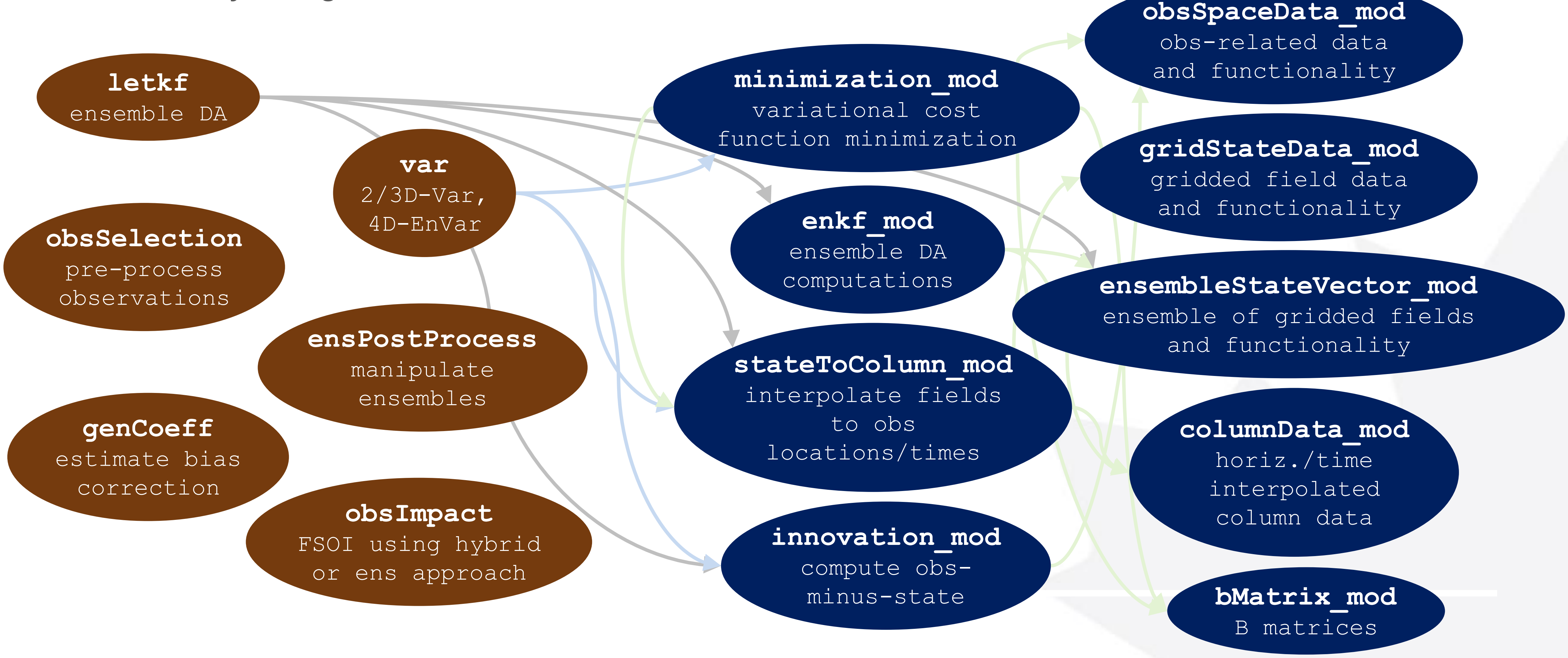
- Disadvantages:
  - Big change from the current system – implementing small incremental changes much easier
  - Decreased flexibility: all components must share common DA time window, observation cutoff time, time slot to run on the computer, use the same assimilation software, etc.

MIDAS: Modular and Integrated Data Assimilation System

- MIDAS is a unified assimilation software framework for research and operational use at ECCC with the objective of:
  - Avoid redundant work within the organization
  - Facilitate transition towards coupled data assimilation of different Earth system components
- Modular and generalized implementation of DA elements (i.e. **H**, **R**, **B**, **x**, **y**) enables use of DA algorithms for various applications (i.e. atm, sea ice, ocean) using mostly the same code
- MIDAS currently includes:
  - Variational assimilation algorithms: 2/3D-Var, 4D-EnVar (for operational NWP)
  - LETKF of various flavours, ensemble inflation and recentering (for operational NWP)
  - Bias correction, QC and thinning algorithms for all operational NWP obs types
  - Assimilation of atmospheric constituents, including ozone
  - Observation impact estimation with hybrid-FSOI and ensemble-FSOI approaches
  - **Sea ice and SST analysis using 2D-Var** → straightforward to test with LETKF/4D-EnVar
  - **Limited 3D ocean assimilation capabilities using LETKF**

MIDAS: Modular and Integrated Data Assimilation System

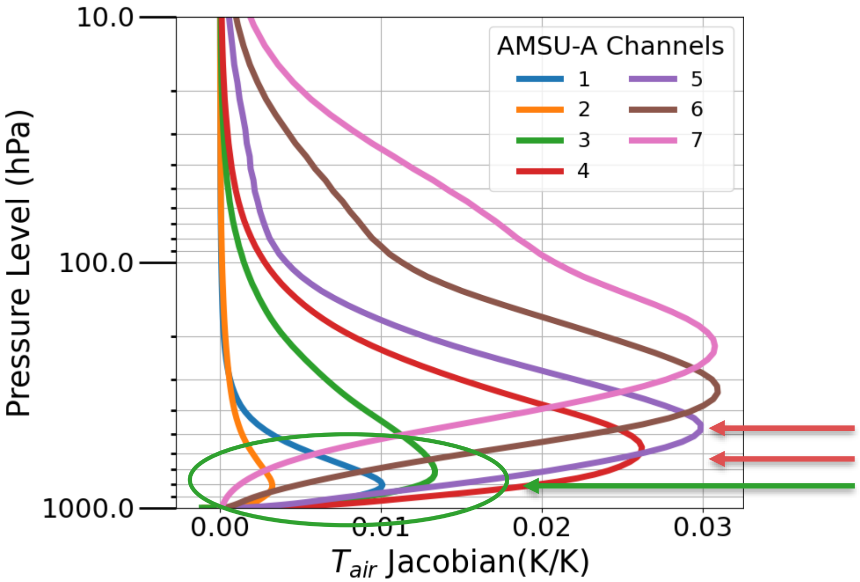
- MIDAS is a collection of ~20 FORTRAN programs that implement all DA-related functionality using more than 100 shared FORTRAN modules:

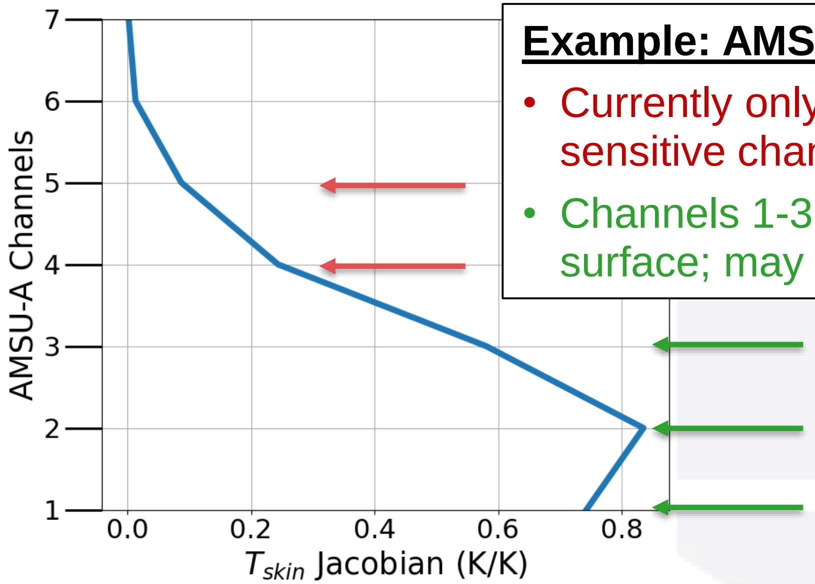


Role of SST in current NWP assimilation systems

NWP need for surface skin temperature over the oceans

- For NWP, surface-sensitive microwave and infrared satellite radiance observations are important atmospheric observations in the lower troposphere over the ocean
- These observations are also sensitive to the surface skin temperature: $T_b = \boldsymbol{H}(T_{air}, T_{skin})$
- Using SST analysis for assimilating these observations may not be accurate enough to provide optimal atmospheric temperature/humidity corrections → T_{skin} errors cause T_{air} errors
- Instead, use SST analysis as background and compute T_{skin} analysis increment along with T_{air} in 4D-EnVar/LETKF (but T_{skin} increment <u>not used for forecast</u>) – like Frolov et al. (2020, MWR)





<u>Example: AMSU-A Microwave radiances</u>

- Currently only assimilate surface-sensitive channels 4 and 5.
- Channels 1-3 strongly affected by the surface; may help constrain near-sfc T_{air}

Different types of "SST"

- Important to distinguish between different types of "SST":
  - Daily SST analysis typically aims to provide "foundation" SST, unaffected by diurnal cycle
  - Surface-sensitive radiance observations are related to surface "skin" or "subskin" temperature
- Akella et al. (2017, QJRMS) used a model to relate T_{skin} to foundation temperature for assimilating surface-sensitive radiances – provides improved fit to observations

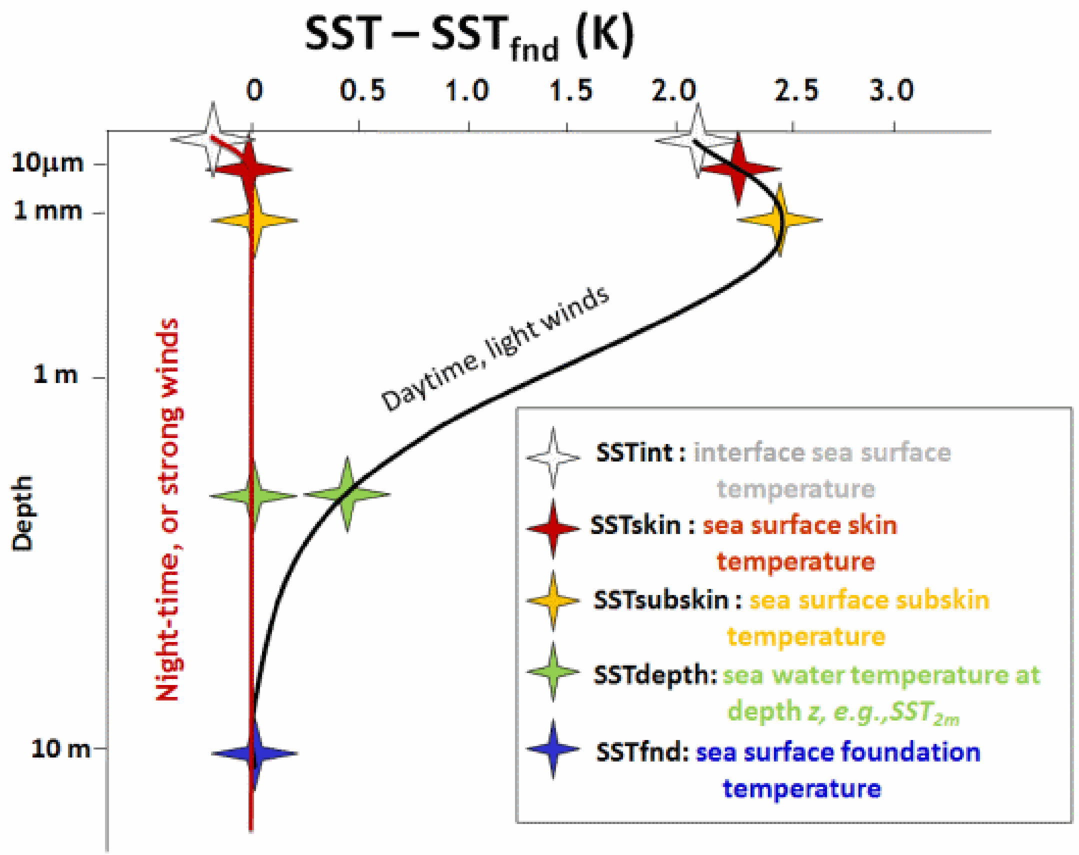
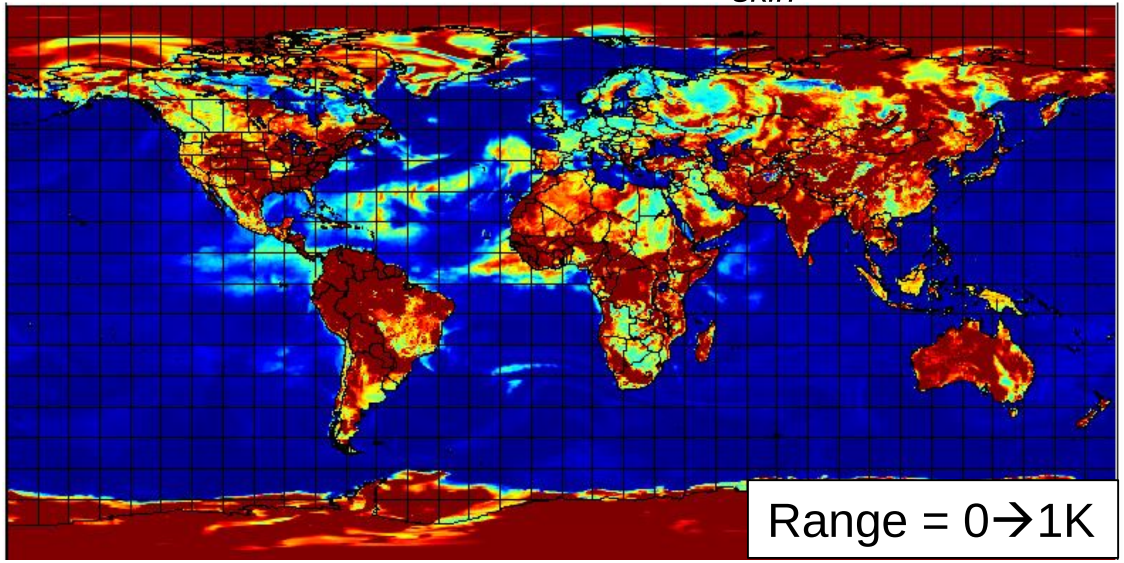


Fig. from https://www.ghrsst.org/ghrsst-data-services/products/

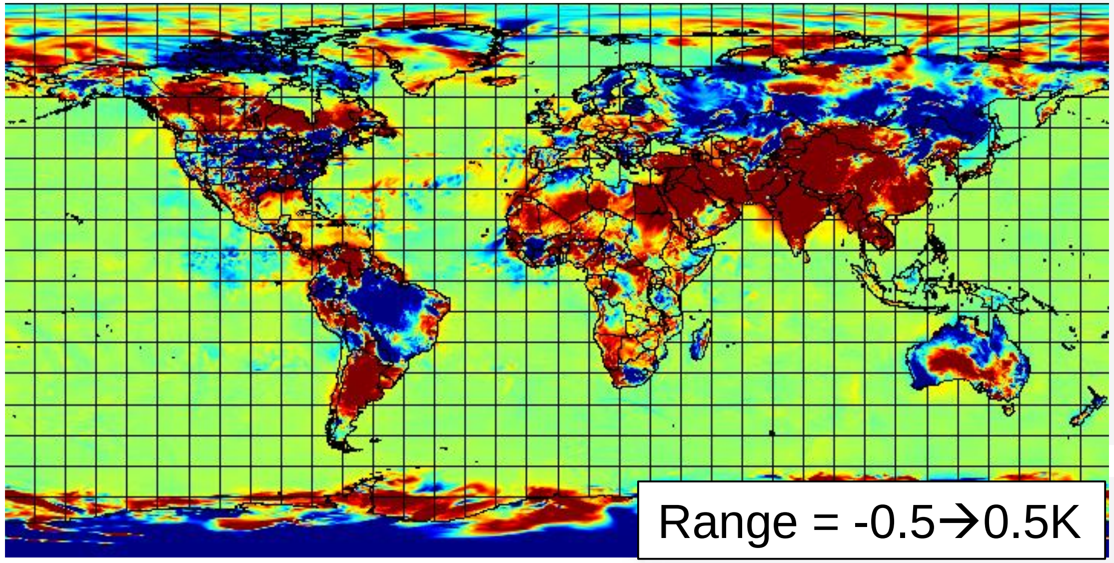
Example of T_{skin} increments from atmospheric observations

- GEPS has little ensemble spread for ocean T_{skin} → all members use same SST analysis; spread only from ocean surface layer parametrization within GEM, no foundation SST uncertainty
- Low ensemble spread results in unrealistically small T_{skin} increments when assimilating surface sensitive radiance observations in 4D-EnVar and LETKF
- These T_{skin} increments are very different than daily SST increment from SST analysis system
- Coupled ocean-atm covariances with realistic SST spread should allow better T_{skin} (SST) analysis within NWP DA and improved/expanded use of surface-sensitive radiances

Ensemble stddev T_{skin}



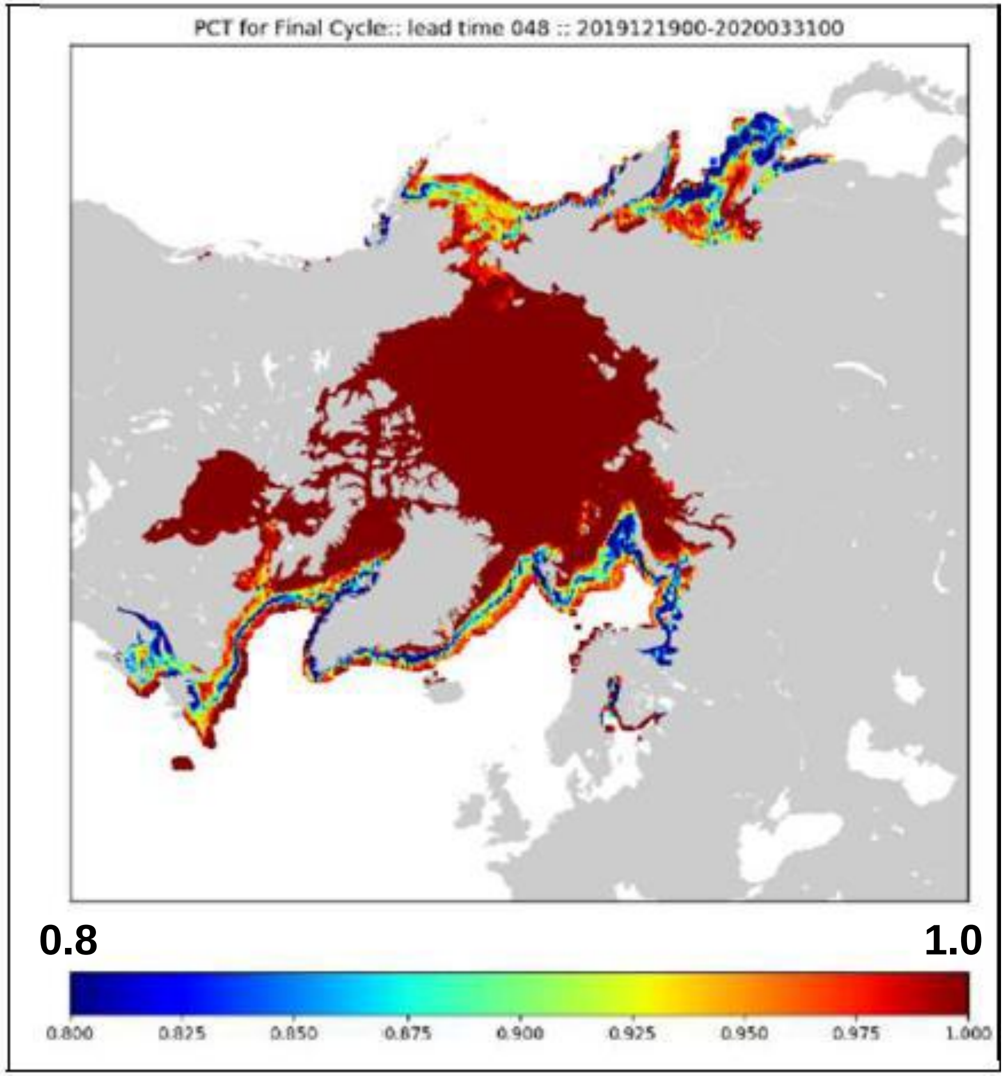
4D-EnVar analysis increment T_{skin}



The ECCC sea ice analysis

Sea-ice analysis at ECCC

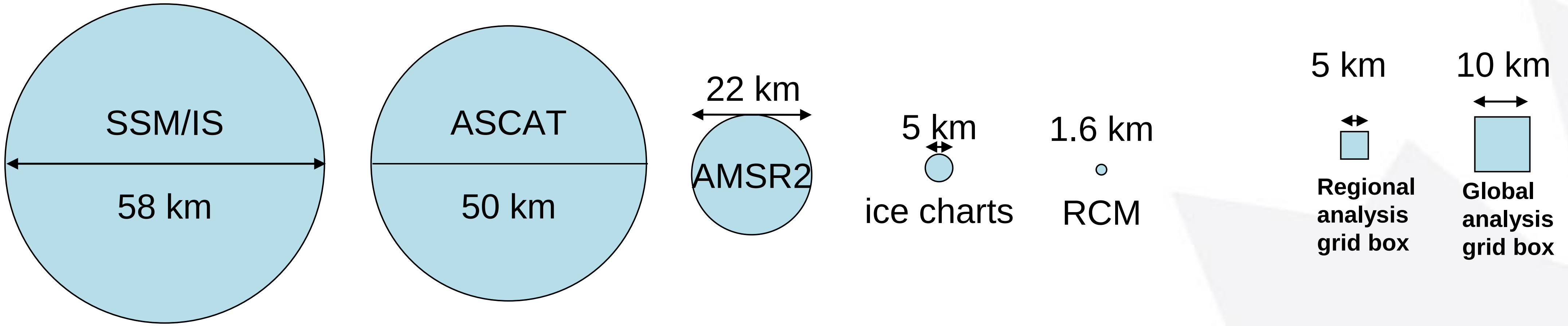
- Ice concentration analysis produced every 6h on both regional and global grids
- Used in NWP and Ocean prediction systems
- Based on 2D-Var approach with horizontal background-error correlations modelled using a diffusion operator
- Also produce analysis error estimate using a simple OI approach to provide measure of uncertainty
- Recently migrated into MIDAS, making use of many existing Fortran modules
- Also developing ice type and ice thickness analyses



Proportion correct (vs IMS) of 48h RIOPS ice concentration forecasts during winter 2019/2020

Sea-ice observations assimilated

- Assimilate observation types with wide range of spatial resolution for estimating ice concentration: SSM/IS, ASCAT, AMSR2, ice charts, and now SAR (in RIOPS only) from RadarSat Constellation Mission (RCM)
- For low-resolution observations, observation operator aggregates ice concentration from all grid points within the observation footprint to avoid constraining unresolved small scales (could be used also for producing high-resolution SST analysis)

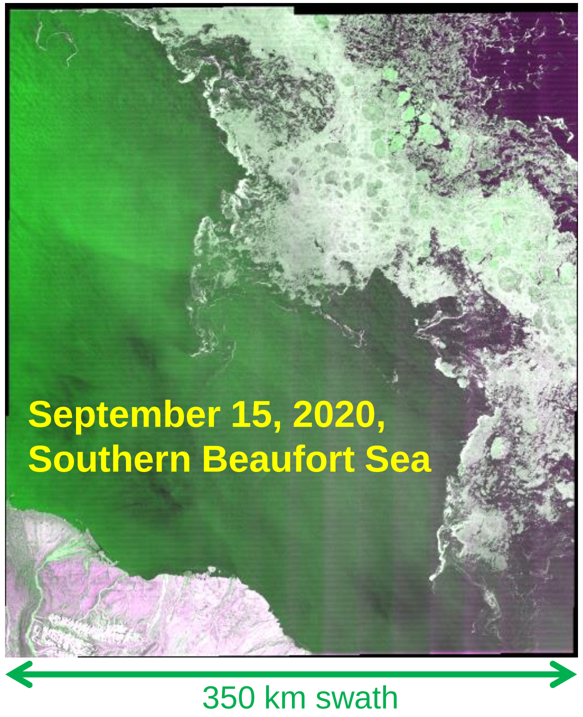


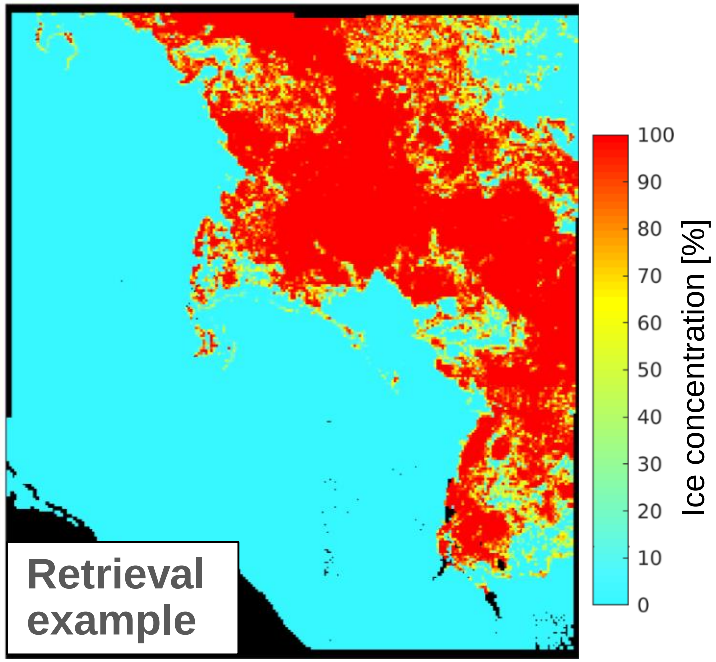
Project of Alain Caya

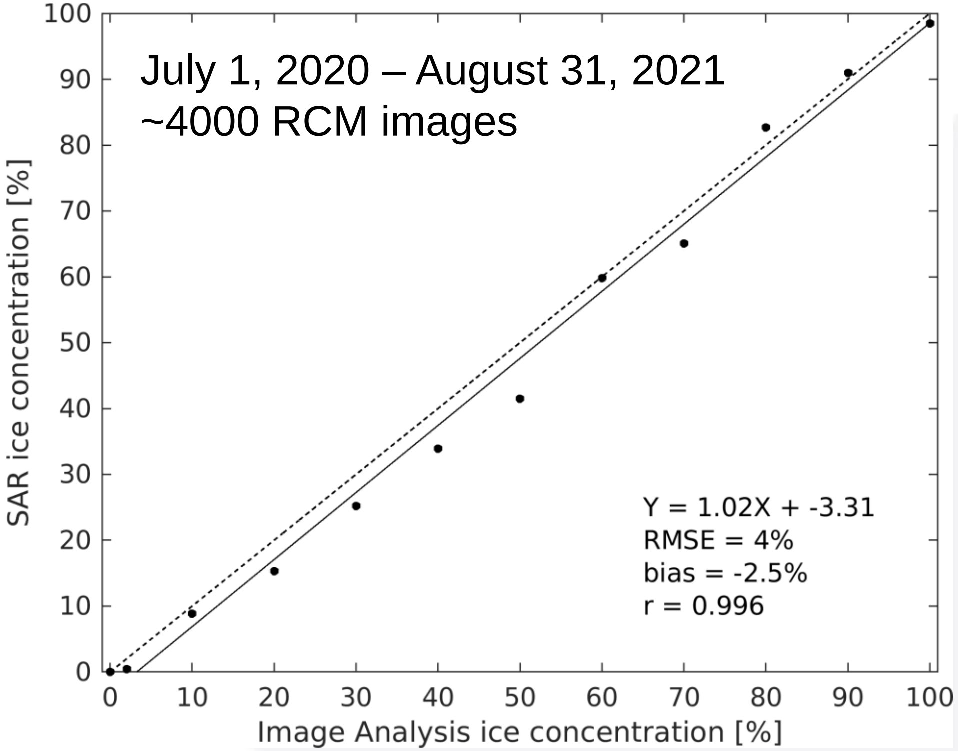
High-resolution ice information from RCM/SAR

RadarSat Constellation Mission (RCM), Synthetic Aperture Radar (SAR)

- SAR data provides very high-resolution and all-weather ice information, but image ambiguities pose serious challenge for fully automated use
- When assimilated with existing obs types, improvement observed where high spatial resolution is important and where CIS ice charts not available



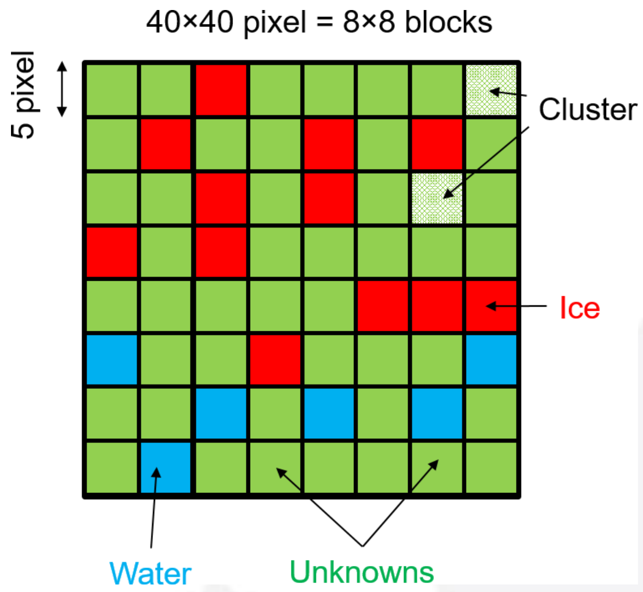




Project of Alex Komarov

Ice concentration retrieval

- Retrieval approach developed based on 15,000+ RADARSAT-2 HH-HV images and CIS ice charts (2010-2016) [Komarov and Buehner, TGRS, 2017], [Komarov and Buehner, GRSL, 2018]



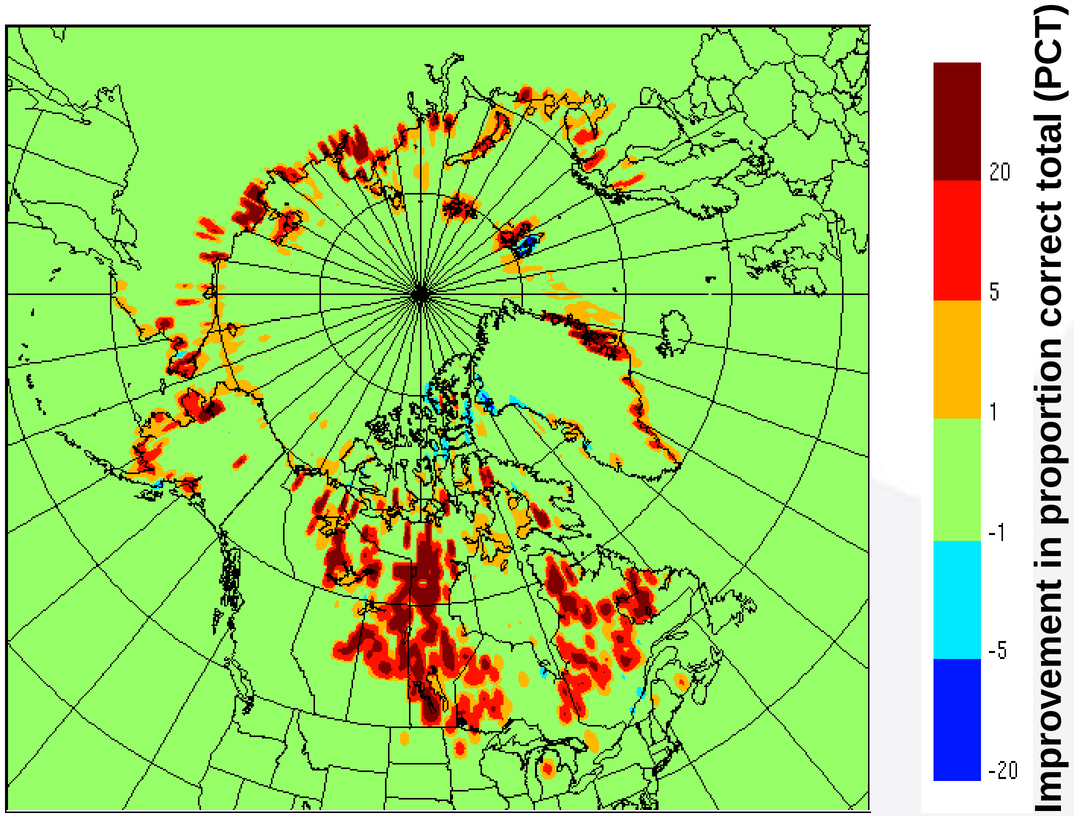
- Probability of ice presence at different scales from 5 x 5 pixels to 41 x 41 pixels (1 pixel = 40 m) calculated as function of three predictor parameters: (1) difference between SAR and NWP wind speed, (2) spatial correlation between HH and HV channels, (3) standard deviation of SAR wind speed [Komarov and Buehner, TGRS, 2020]

- The approach was adapted from RADARSAT-2 to RCM by introducing the new ocean surface wind speed retrieval models developed for different RCM beam modes [Komarov et. al., TGRS, 2022]

Assimilation of RCM ice concentration - Verification against IMS

August 1, 2020 – July 31, 2021

- SAR retrievals from ~65,000 RCM images over a year period
- Main improvements near land, over lakes, marginal ice zones and where CIS ice charts not available



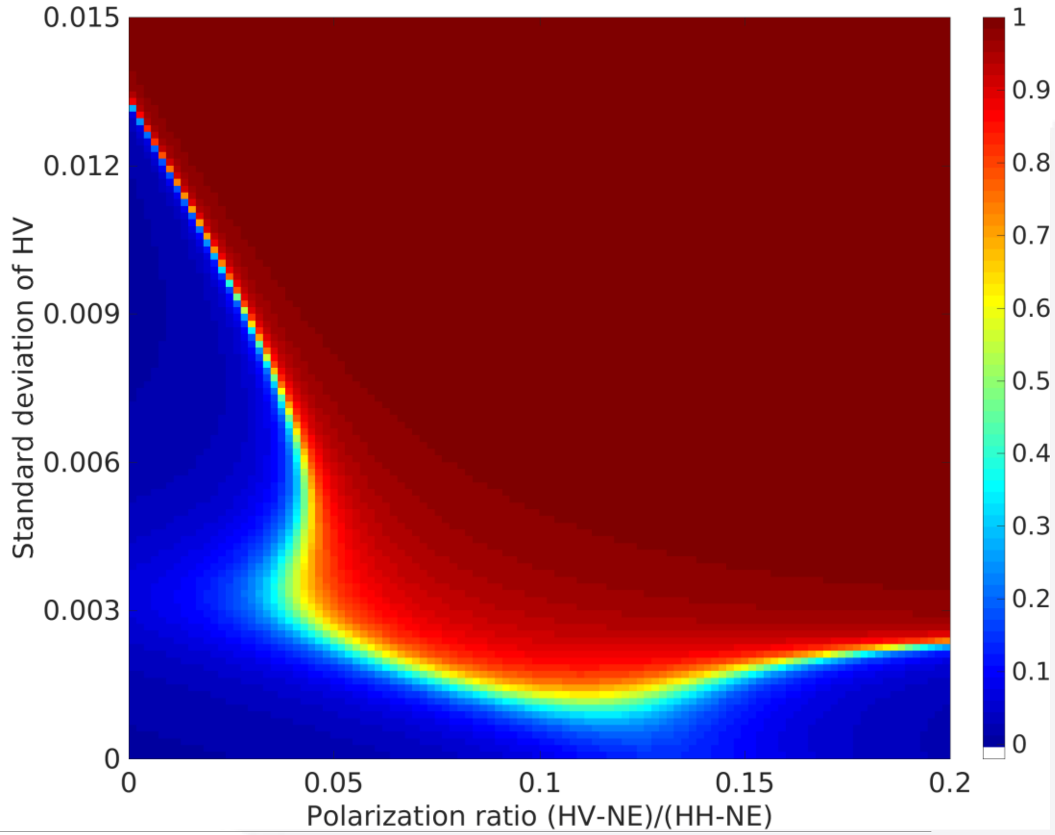
Ice type retrieval from RCM data

- Compute empirical probabilities for two ice types: first-year and multi-year ice
- The technique is applicable under cold conditions for HH-HV SAR images
- Probabilities computed for 2 predictors:

  (1) HV/HH polarization ratio

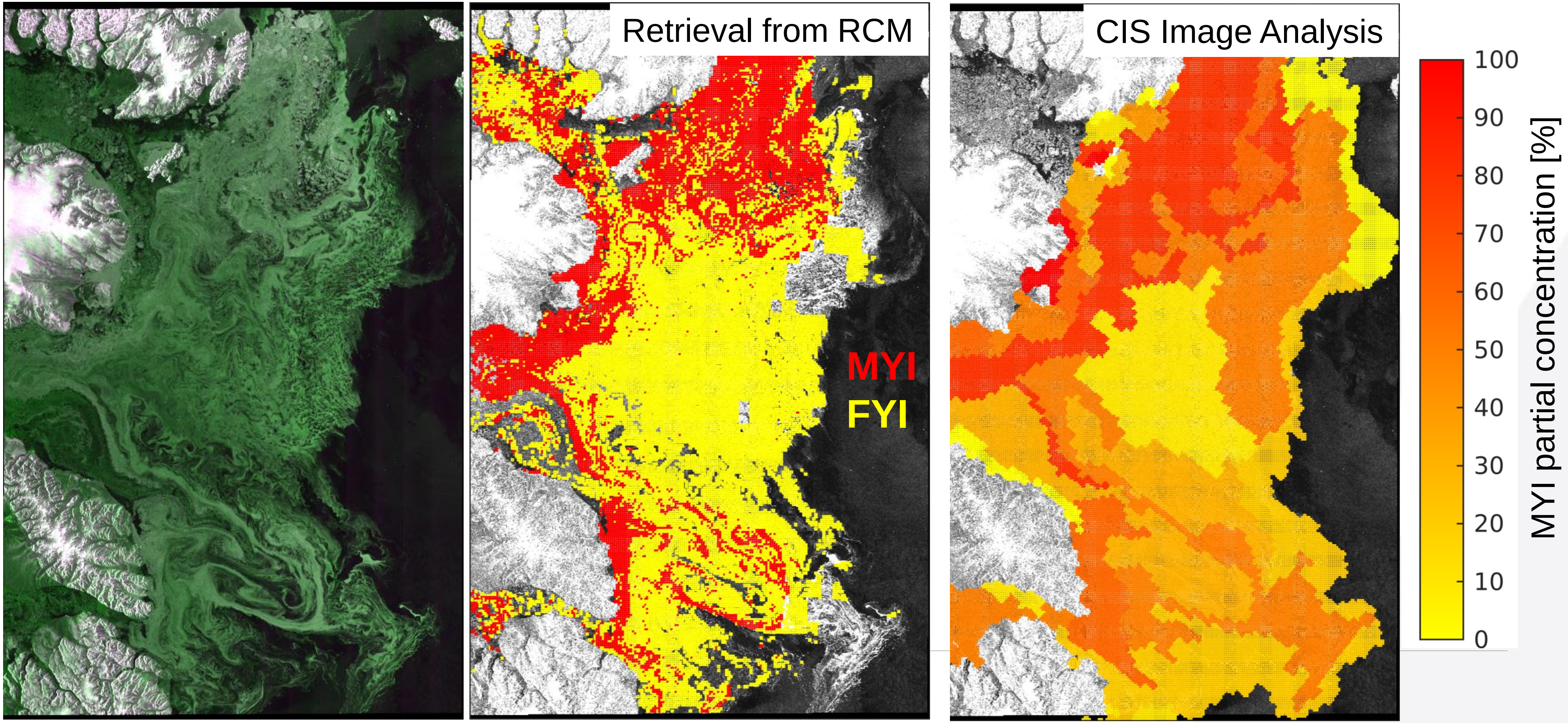
  (2) standard deviation of HV
- High overall accuracy for MYI (96.4%) and FYI (99.7%) against CIS image analyses

Probability function of MYI from RADARSAT-2 (2010-2016)



Komarov, and Buehner, 2019, *IEEE Trans. Geosci. Remote Sens.*

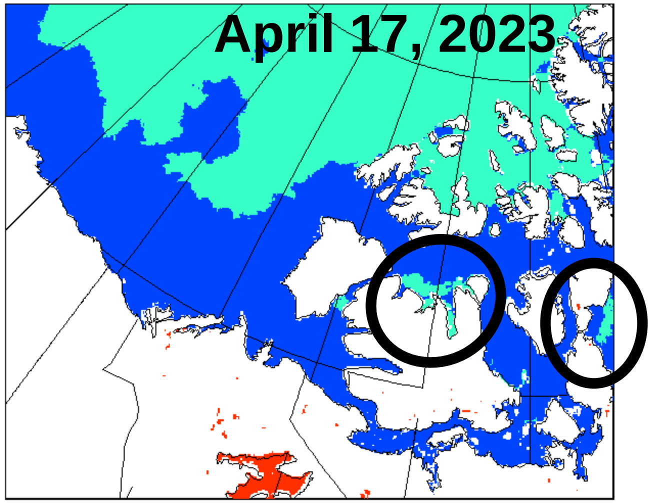
Ice type retrieval example (Oct. 19, 2022)



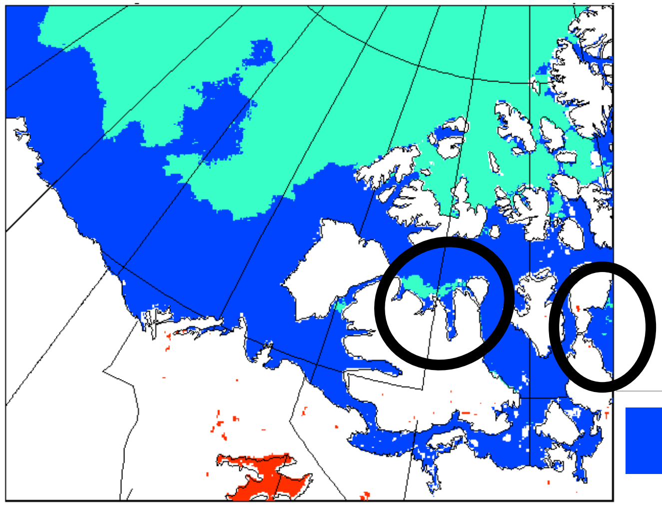
Assimilation in Ice Type Analysis System

- Impact of using RCM in addition to low-resolution passive microwave and scatterometer data
- Ice type analysis used as input for ice thickness retrieval from CryoSat and SMOS/SMAP

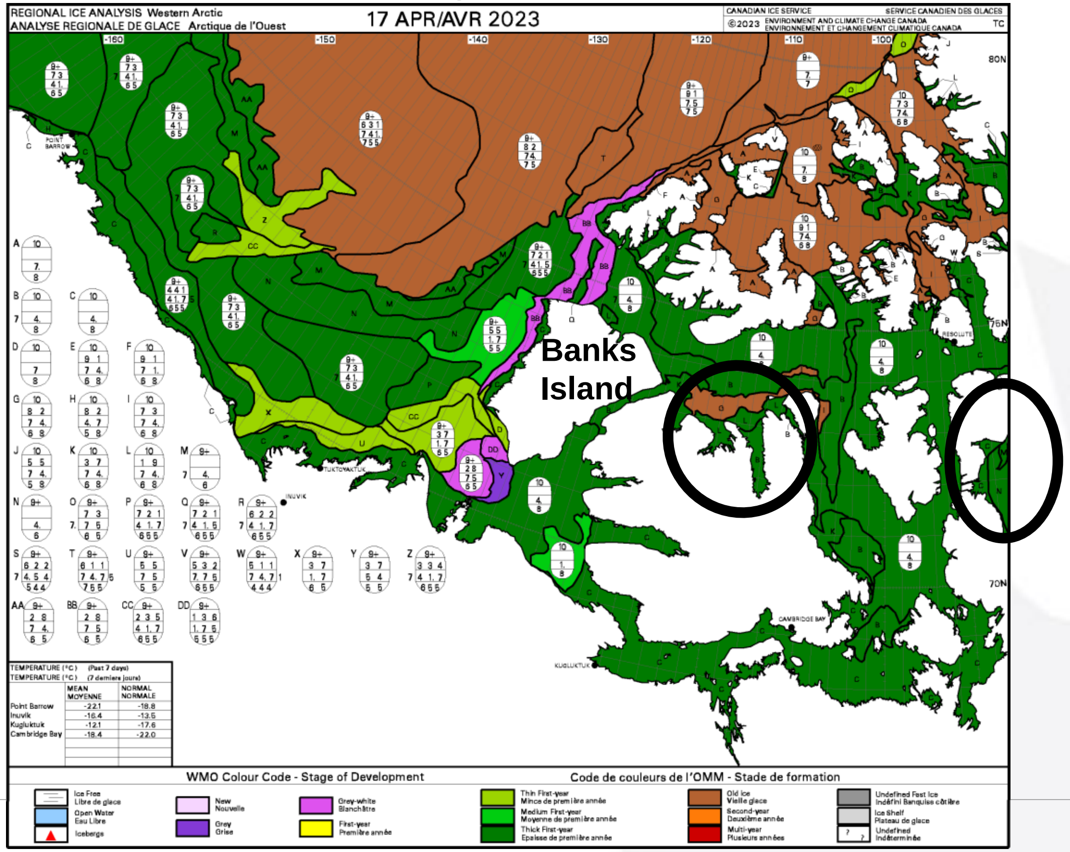
Analysis with no RCM



Analysis with RCM

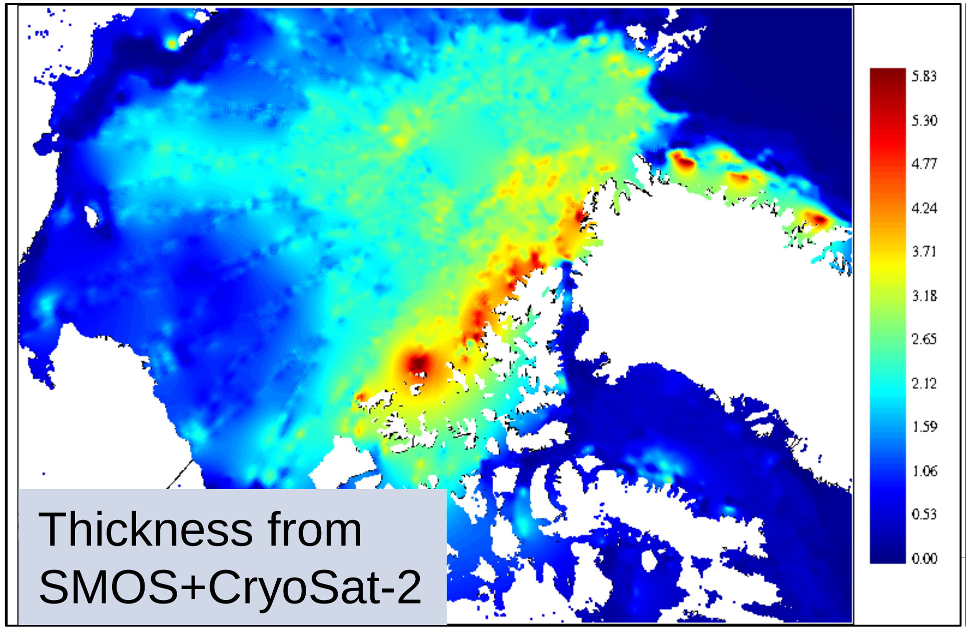


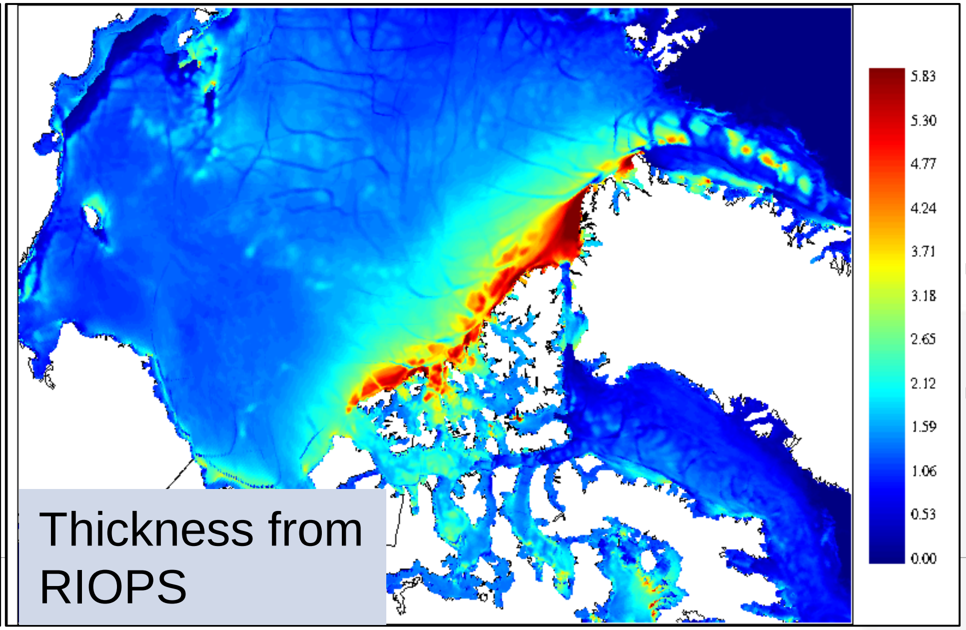
CIS regional chart



Ice thickness analysis

- Using 2D-Var to assimilate ice thickness retrievals from SMOS (for thin ice) and CryoSat-2 (for thicker ice) to produce ice thickness analysis
- Comparison with the (unconstrained) thickness of current ice-ocean prediction system shows many differences
- Evaluating both with respect to independent "IceBridge" observations, shows thickness analysis could improve model thickness for ice in the range of: 2m–3.5m



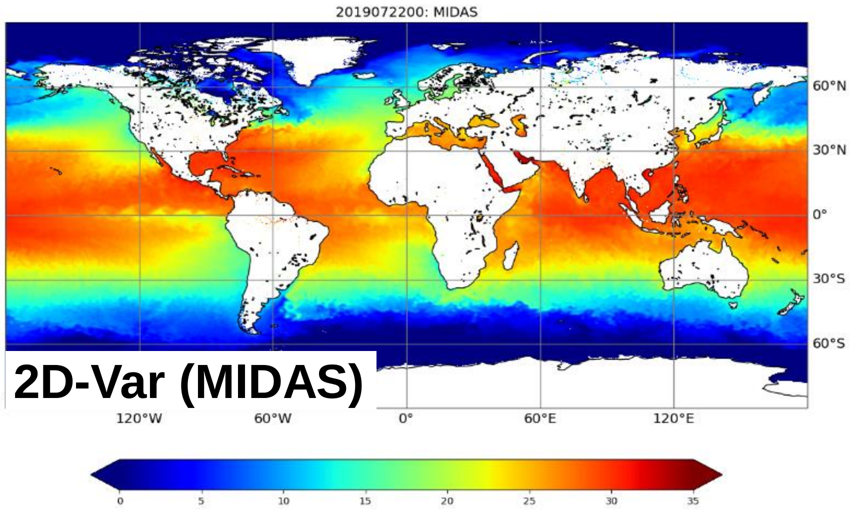


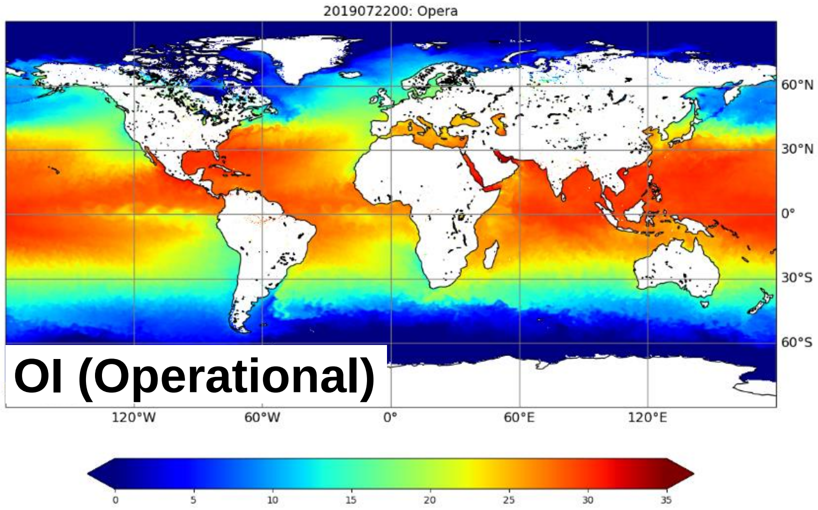
} Range where analysis more consistent with "IceBridge" than the model

SST, ocean and coupled assimilation

New MIDAS-based SST analysis

- Operational system based on optimal interpolation (OI) with old-style Fortran code
- Like for sea ice, MIDAS-based system uses 2D-Var with diffusion operator **B**-matrix
- Ability to assimilate SST observations in MIDAS creates new possibilities related to coupled data assimilation that could reduce need for stand-alone SST analysis:
  - SST obs can be assimilated in a MIDAS-based 3D ocean assimilation system
  - SST obs can be assimilated in the NWP assimilation system in addition to existing atmospheric observations





See talk by Sergey Skachko

3D ocean assimilation with MIDAS-LETKF

- 3D ocean assimilation could use existing MIDAS algorithms: LETKF or EnVar
- Implementation on the NEMO ORCA grid simpler with LETKF than EnVar:
  - Covariance localization in LETKF only requires ability to compute distances between observations and grid points
  - Covariance localization implemented in EnVar using spectral transform on a Gaussian global grid – interpolation between grids could be problematic near coastlines
- Initial tests use ensembles from existing 20-member coupled forecasts, recentered on deterministic state → LETKF produces a deterministic analysis
- Now preparing the full system suite to enable daily cycling of LETKF with an ensemble of NEMO-CICE forecasts forced by atmospheric ensemble system

3D ocean assimilation with MIDAS-LETKF

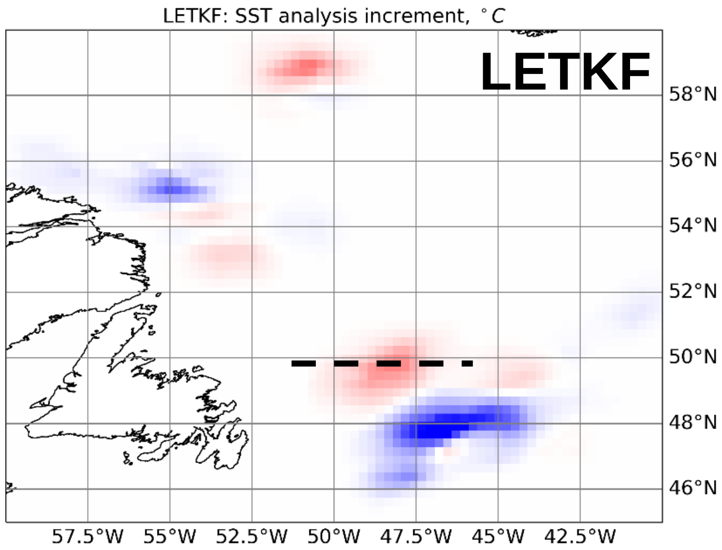
Example:

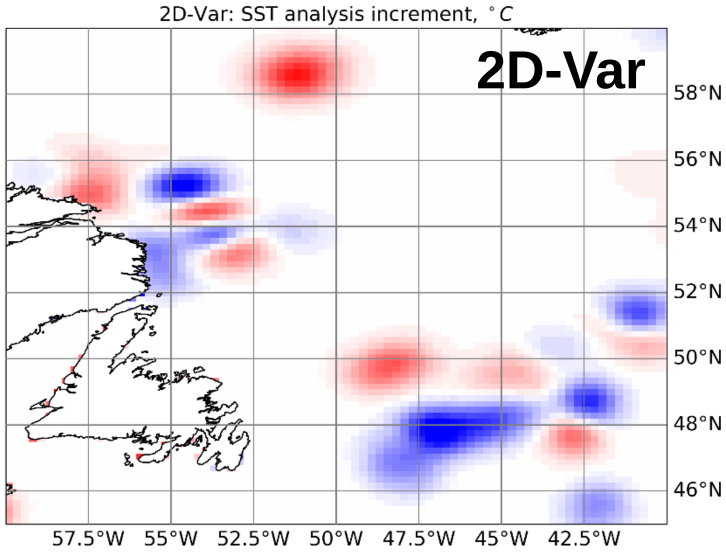
LETKF ensemble mean SST increment vs. 2D-Var

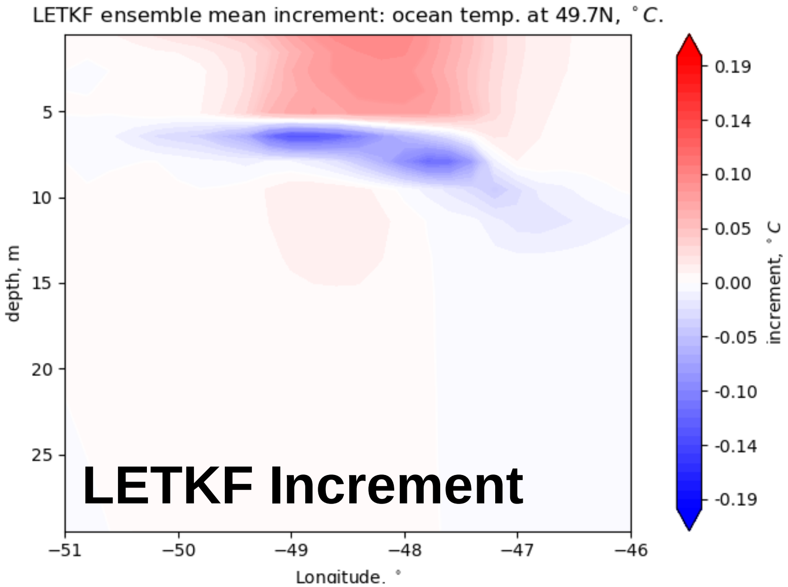
Assimilating **only in-situ SST** observations

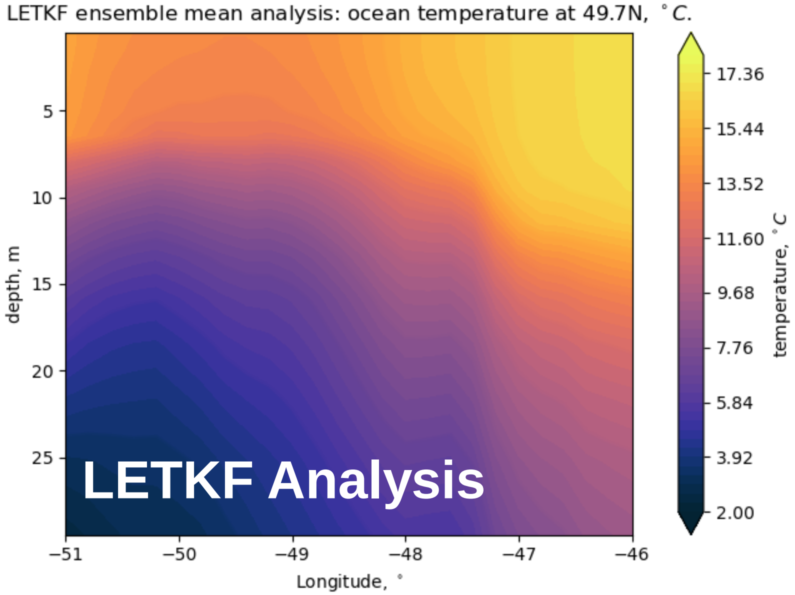
LETKF in this example uses 20-member ocean ensemble from operational coupled forecasts

Realistic looking increment consistent with shallowing of mixed layer near Nfld





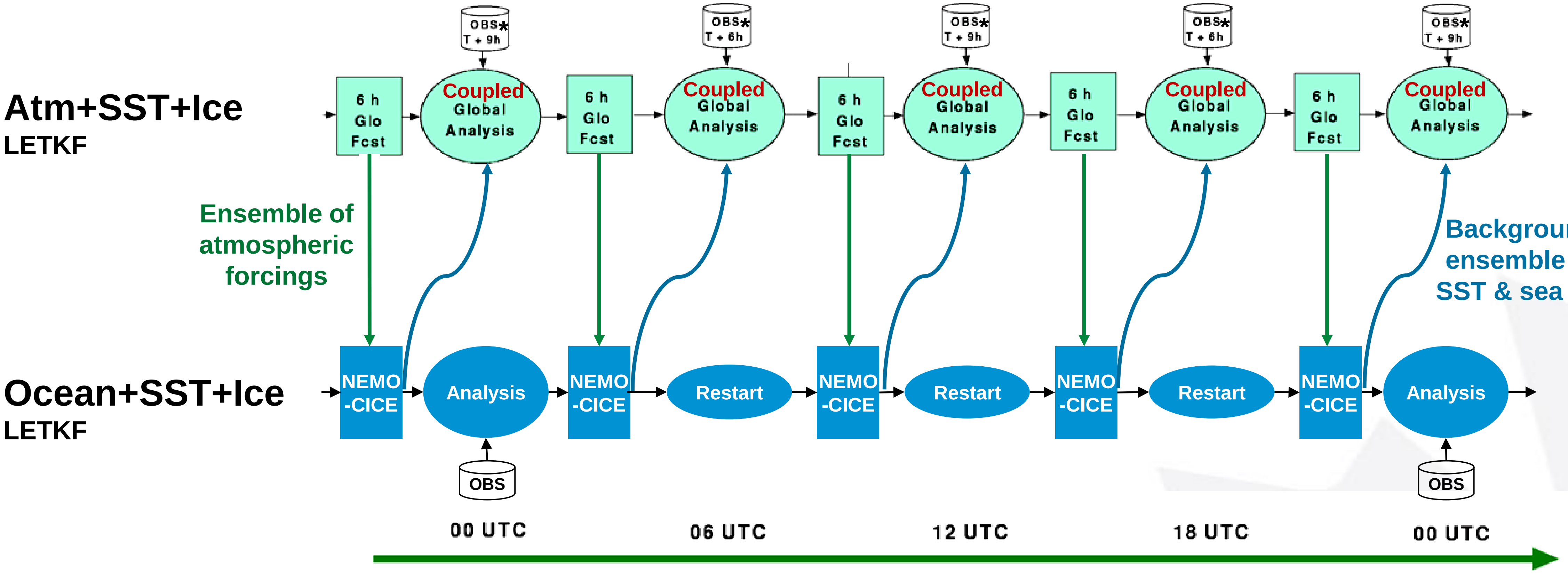




Towards coupled DA – building on ocean LETKF

- Possible intermediate step – similar to interface solver of Frolov et al. (2016):
  - Ensemble of atmospheric model integrations use SST (and sea ice) ensemble valid at the initial time and held constant through short-term forecast
  - Ensemble of ocean model integrations forced by atmospheric members
  - Same SST (and sea ice?) obs assimilated in both the NWP and ocean assimilation systems, removing need for separate SST analysis system
- Benefits of approach:
  - Maintain more realistic SST (and T_{skin}) ensemble spread in NWP assimilation cycle, improving use of existing surface-sensitive atmospheric observations
  - More flexible than fully coupled DA cycle → model and assimilation still separate for ocean and atmosphere
  - After establishing a MIDAS-based ocean LETKF, this small incremental change should bring many (but not all) coupled assimilation benefits to the NWP system

Towards coupled DA – building on ocean LETKF



Summary and future research

- Increasing use of MIDAS at ECCC for ocean and sea ice will improve efficiency of developing/maintaining DA systems for each Earth system component, while also making **research on strongly coupled assimilation** possible
- Sea ice and SST analysis system already in MIDAS, **next step is full 3D ensemble ocean analysis**
- Interface solver approach is an incremental step towards full coupling; interface obs assimilated in both systems, easy with both systems using MIDAS-LETKF