Section 9

Development of and studies with coupled and Earth system models and data assimilation systems.

Coupling of oceans and land surfaces in the ECMWF Integrated Forecasting System: Sensitivity and impact of diurnal and synoptic variability on medium-range skill

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The benefits of coupling the ocean and land modeling components to the ECMWF medium-range forecasts are evaluated in a set of dedicated forecast sensitivity experiments. The ocean model (NEMO v3.4) in the ORCA025_Z75 configuration includes 75 vertical layers and a ¼ degree horizontal resolution to represent the 3D ocean and includes a dynamical sea-ice model (LIM2) and a wave-model (EC-WAM). The land-model includes the HTESSEL 4-layer soil scheme and 1-layer snow scheme plus a mixed-layer lake model. In uncoupled sensitivity runs the diurnal cycle is ensured only by a skin layer parameterization while in coupled runs NEMO and HTESSEL are providing tendency updates interactively responding to the meteorology. A full year of daily medium-range forecast experiments are performed. These sensitivity runs highlight the day-5 forecast is largely affected by surface-atmosphere coupled processes and show how land and ocean are complementary in providing diurnal and synoptic variability contributing to enhanced forecast skill.

Modelling components

The ECMWF Integrated Forecasting System (IFS Documentation, 2017) cycle 43r3 operational from the 11th of July 2017 is used. This employs a cubic octahedral reduced Gaussian grid (Wedi, 2014) that is used for operational ECMWF forecasts of the ensemble prediction system, labeled ENS (at 18 km resolution) and its bi-weekly Monthly extension (at 36 km resolution), a high-resolution system labeled HRES (9 km resolution) and a new seasonal forecasting system named SEAS5 (at 36 km resolution).

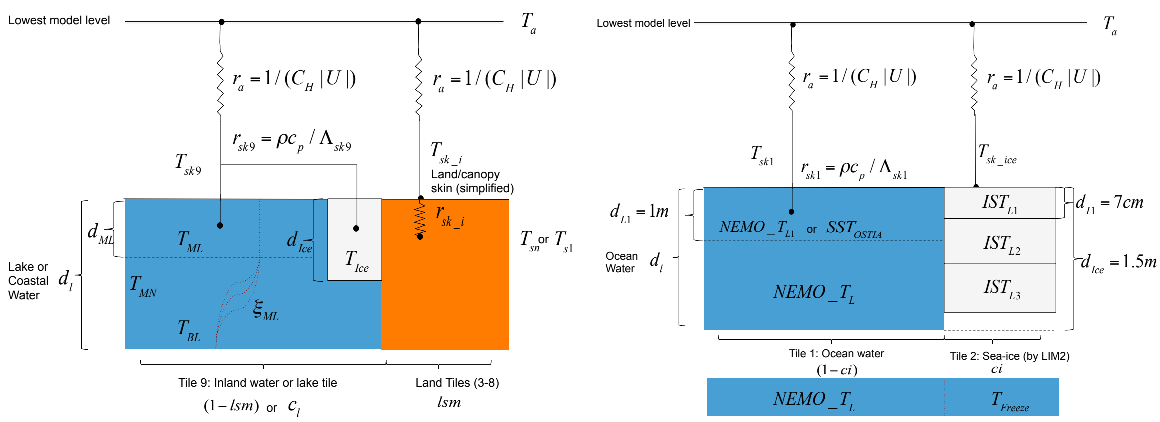

Figure 1: Schematic representation of the land-lake-ice coupling (left) and ocean-sea-ice (right) in the ECMWF Integrated Forecasting System (for details and symbols' legend see IFS documentation, Part-IV, 2017).

The NEMO v3.4 ocean model is used with horizontal resolution of 0.25 degree globally applied to all the atmospheric configurations listed above. The number of horizontal grid points in the ocean (1472282) is fixed in all coupled forecasts configurations. The 75-layer vertical ocean column has fine scale discretization in the upper ocean (1m) able to represent the mixed-layer and the diurnal cycle variability. The LIM2 sea-ice model evolves the sea-ice cover and is able to respond to the changes to the atmosphere and ocean states e.g. melting of sea-ice during atmospheric warming in spring.

The land-surface model used in the ECMWF forecasting applications is HTESSEL, that stands for Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land, and it include a 4-layer land-surface hydrology (Balsamo et al. 2009, Albergel et al. 2012), a 1-layer snow scheme (Dutra et al. 2010), a vegetation and natural carbon cycle scheme (Boussetta et al. 2013) and an embedded mixed-layer scheme for subgrid water bodies (Manrique-Suñén et al. 2013).

Initialization procedure

The implementation of the ORCA025_Z75 for the ENS system is dependent on having good ocean initial conditions available. A lot of work has gone into developing the new operational ocean reanalysis system 5 (OCEAN5, based on ORAP5 documented in Zuo et al. 2015). It uses a 3D-VAR assimilation (NEMOVAR, Mogensen et al. 2012) to produce daily initial conditions for the ORCA025_Z75 configuration in both real time and behind real time mode. The sea surface temperature (SST) initialization of the atmospheric model is a combination of the NEMOVAR ocean model state and high resolution OSTIA SST product (Donlon et al., 2011). The ocean model can be considered to resolve eddy features within the tropical region and therefore the tropical SSTs are directly coupled to the atmosphere while for the extra-tropics a tendency update is adopted for the first week of the forecasts to make use of the high resolution features of satellite based SSTs products. The land surface initialization takes care of the soil moisture, soil temperature and snow depth via the Land Data Assimilation System at ECMWF (de Rosnay et al. 2014) that makes use of conventional ground-based observations (e.g. SYNOPs reports) and satellite dataset (e.g. IMS snow cover and ASCAT soil moisture).

Coupling experiments

In the IFS forecast integrations with the coupled system the information from/to ocean/atmosphere is exchanged with a coupling frequency of 1-hour while the land is updated at every time-step (varying from 7.5 minutes to 60 minutes in the different configurations). The ocean coupling includes feedbacks from wind waves to both the atmosphere and the ocean as described in Janssen et al. (2013). When the ocean model is uncoupled the waves are still active but the SST variations are represented by a warm-layer parameterization (Takaya et al. 2010). The cryosphere-atmosphere coupling adopts an explicit flux coupling with a stability control that mimics fully implicit formulations (Beljaars et al. 2017). The land surface tiling (Figure 1) ensures the coupling of ocean and sea-ice information to the atmosphere and permits fractional ocean/ice contributions to the energy fluxes. The coupling of the sea-ice cover information is passed from the LIM2 model to the IFS with an ice-to-ice coupling that updates the ice/sea fractions hourly. The thermodynamics of ice is computed separately in both IFS and LIM2 for practical reasons, and this will be the subject for research in the near future.

Forecast sensitivity and impact

Medium-range performance has been evaluated in a set of forecasts experiments using the operational HRES analysis (9km) as verifying term. Forecasts impact is highlighted in Figure 2 for a selection of meteorological quantities.

The capacity to forecast interactively ocean and sea-ice conditions following atmospheric conditions and the benefits are particularly evident in tropical surface pressure, tropospheric temperatures and humidity. Tropical winds confirm an impressive signal throughout the troposphere and the lower stratosphere, attributed to improved simulations of the Hadley and Walker cells. These improvements (blue colors) are quantified in 5 to 10 % error reduction of the day5 forecasts of mean sea level pressure and geopotential height at 500 hPa and smaller but significant improvements also in wind speed and relative humidity (of the order of 2 to 4 %).

The average improvements evaluated over a full year of forecasts are also found in improved medium-range forecasts of extreme events, such as tropical cyclones (Mogensen et al. 2017), with an error reduction both in cyclones location and intensity particularly evident from day 5 to day 10 (not shown).

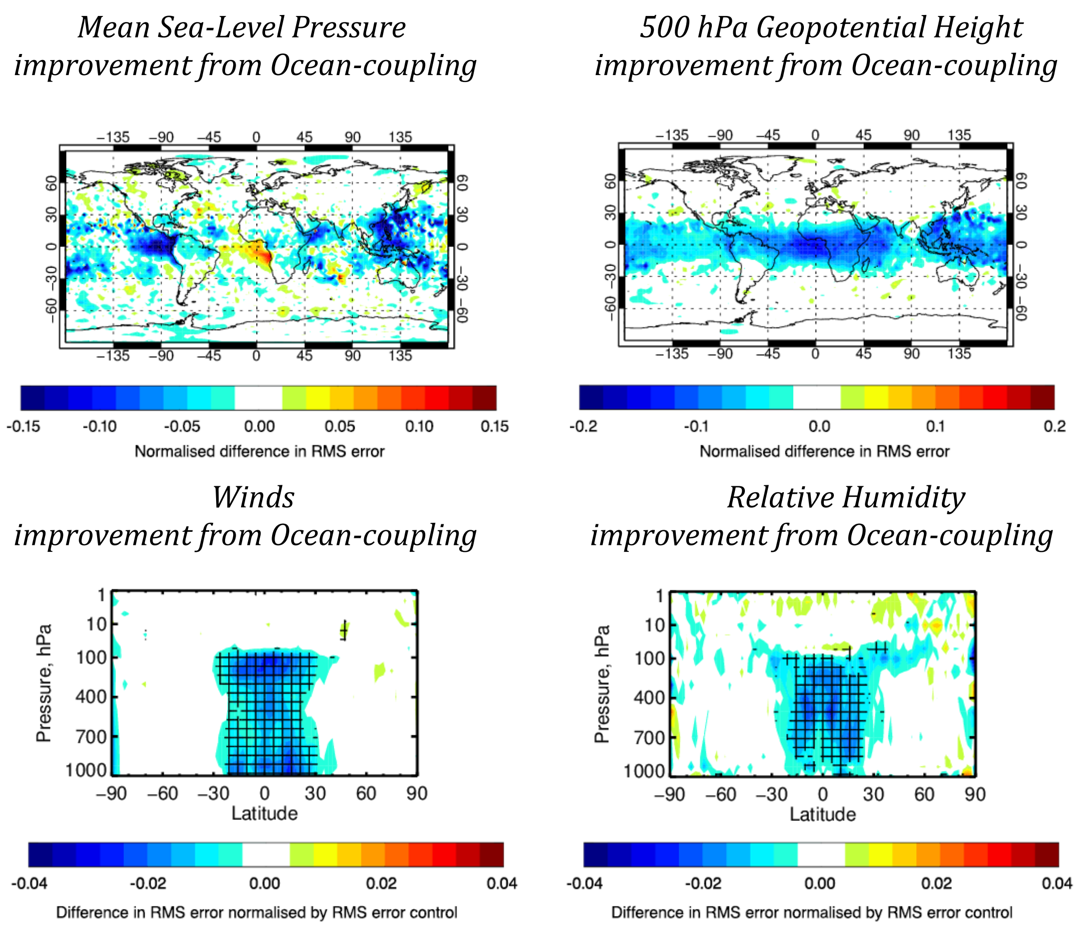

Figure 2: Forecast improvements at Day+5 (blue colors indicating RMS error reduction) due to the HRES coupling of the NEMO+LIM2 Ocean and sea-ice model to the atmospheric model integrations, evaluated on one full year of TCo1279 daily forecasts (April 2015-March 2016) in 4 meteorological fields. Significance at 95% confidence level is reached for the shaded regions in the cross-sections (lower panels, shaded areas).

Over land, where longer NWP operational experience is accumulated at ECMWF, the importance of representing the diurnal cycle amplitude and the synoptic variability in coupled land-atmosphere integration is illustrated by dedicated process-suppression experiments. The land surface model variables describing soil, snow, lakes evolution are neglected along the forecast and improvement bought by coupled land-atmosphere forecasts is measured (in analogous way as done for the ocean). This experiment allow to evaluate in analogous terms the impact of diurnal and synoptic cycle variability brought by land surface coupling that is shown to be of high relevance for tropospheric temperatures with large impact also on circulation Figure 3.

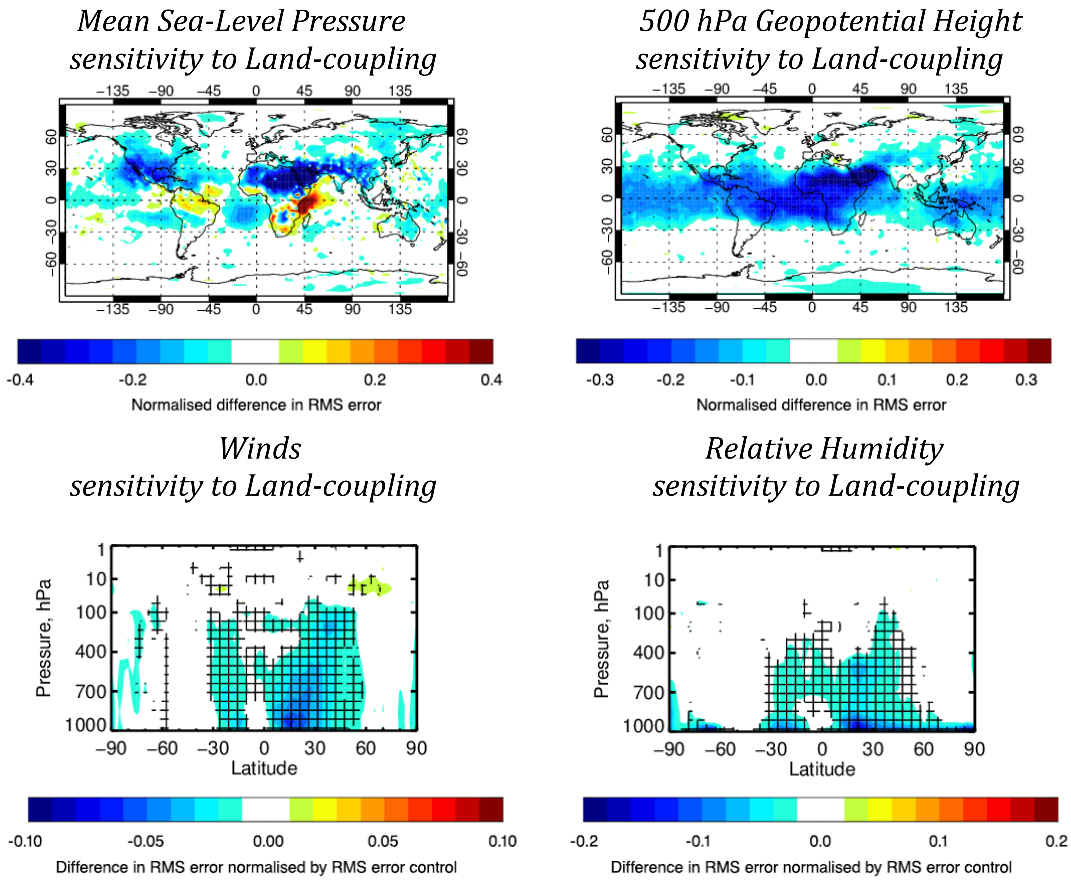

Figure 3: Forecast sensitivity at Day+5 (blue colors indicating RMS error reduction) due to the land surface coupling to the atmospheric model integrations, evaluated on one full year of TCo399 daily forecasts (June 2015-May 2016) in 4 meteorological fields. These are analogous scores to Figure 2.

The land and ocean coupling determine a forecast skill improvement of similar magnitude at day-5 and the complementary aspects are evident both geographically and in vertical cross-sections showing the propagation of surface conditions throughout the atmosphere and up to 100 hPa pressure level extending the forecast sensitivity from 30S to 60N.

Summary and outlook

The coupling of oceans and land surface models at ECMWF and the benefit on synoptic and diurnal cycle variability are estimated in sensitivity experiment. A more coupled Earth System model is shown to improve the forecast in the medium range. The ocean experiments are part of the current effort to introduce ocean-atmosphere coupling, making best use of the new NEMO 3D-ocean dynamics to predict ocean variability in sea surface temperature and energy-momentum exchanges. The land-coupling experiments are produced to measure the impact of land surface variability and allow a comparative assessment of the important of modeling these Earth surface components and provide evidence for handling atmospheric coupling in seamless manner.

The benefits usually attributed to surface initial conditions are present in both setups therefore the signal can be attributed to the modeling components. Advantages of ocean coupling are evident also for the medium-range and therefore led us to pursue a seamless implementation of the NEMO model across all ECMWF forecasts that will be completed in 2017. Further research will explore the importance of ocean wave dynamics and sea-ice interactions and taking up future NEMO upgrades.

For the land surface the high impact of land-induced diurnal and synoptic variability supports further research into heat and water transfer across the snow and soil media and their dependency on land-use and associated properties. For those the use of remote sensing Earth Observations (Satellite-base skin temperature) is shown to have large potential supporting coupling parameters' estimation with impact anticipated for both medium and extended ranges (Orth et al. 2017).

Refinements to the coupling at the surface for both land (snow and soil increased vertical layer discretization) and in the ocean (mixed-layer, sea-ice, wave interaction) will aim at enhancing the realism of the diurnal cycle and the response to synoptic variability. A more integrated fully coupled land-ocean-atmosphere model with reduced systematic errors is a stepping-stone for coupled data assimilation that is expected to enhance further the medium-range forecast skill.

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Subseasonal Forecast Skill of the FIM-iHYCOM Coupled Model

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1 Introduction

Earth-system prediction skill on subseasonal to seasonal timescales is rather limited in the current generation of numerical models. Two types of ensemble prediction have been shown to be effective, to some extent at least, in reducing forecast error: (1) use of an ensemble whose members are diversified by both perturbed initial conditions and stochastic perturbations of model physics in a single model; (2) use of different models in a "multi-model ensemble", all running with perturbed initial conditions. To maximize the gain from ensemble methods, approach (2) requires that special attention be paid to model diversity in order to ensure sufficient spread among ensemble members. This makes models employing nontraditional numerics especially attractive in multi-model ensembles. The coupled model FIM-iHYCOM developed at NOAA's Earth System Research Laboratory falls into this category and is one of the models providing forecasts for NOAA's Subseasonal Experiment.

2 Models and Experiments

The atmospheric model FIM (Bleck et al. 2015), developed as a tool for medium-range to subseasonal prediction, has been coupled to iHYCOM, an icosahedral-grid rendition of the ocean model HYCOM (Bleck 2002). Both FIM and iHYCOM are 3-dimensional hydrostatic gridpoint models that operate on a common icosahedral horizontal grid and use similar adaptive near-isentropic vertical grids. Due to the shared horizontal grid as well as an identical time step, no spatial or temporal interpolation is needed when passing information from one model component to the other. This guarantees conservation, not only globally but also locally, of all fluxes across the air-sea interface. Equally important, there is no discrepancy between the two components on the location of the coastline.

FIM uses the 2015 Global Forecast System (GFS) physics package, with an option of switching its Simplified Arakawa-Schubert shallow and deep convective cloud parameterization to a variant of the Grell and Freitas (2014) scheme (SAS and GF hereafter). Once-per-week subseasonal hindcasts with 4 time-lagged ensemble members over a 16-year period have been carried out with the FIM-iHYCOM coupled model at 60 km horizontal resolution, comparing skills using SAS and GF (FIM-SAS and FIM-CGF, respectively) to the NOAA operational model CFSv2, as well as the GF scheme in uncoupled FIM atmospheric-only mode (FIM-AGF).

To illustrate the icosahedral horizontal grid, Fig. 1 displays the ocean depth around New Zealand at 30 km grid resolution (30 km runs are underway).

3 Results

The Realtime Multivariate Madden-Julian Oscillation (MJO) index (RMM) and velocity potential MJO index (VPM) for various FIM-iHYCOM runs and CFSv2 ensemble mean forecasts are shown in Fig. 2 as a function of lead time, including (top) bivariate RMM correlation, (bottom) bivariate root-mean-square error (solid) and 4-member ensemble spread(dashed). FIM-CGF and CFSv2 have similar skill, error, and spread, and are better than FIM-SAS. The uncoupled FIM-AGF fares worst. Using GF to parameterize deep convection was found to improve the skill of MJO predictions as described in Green et al. (2017).

Fig. 3 compares the Anomaly Correlation Coefficients (ACC) for different lead weeks in boreal summer (June through August, JJA) and winter (December through February, DJF) for the 2 m temperature from FIM-CGF and CFSv2 over land in North America. The ACC is highest at lead times of 1 and 2 weeks, especially in winter. There is some skill beyond 2 weeks, benefiting from averaging both in time (weekly) and space ($5^\circ \times 5^\circ$), compared to daily means and $1^\circ \times 1^\circ$ averaging (not shown).

4 Summary

Preliminary results indicate that the forecast skill of FIM-iHYCOM is comparable to that of NOAA's operational CFSv2 model at the subseasonal time scale. FIM-iHYCOM uses an unstructured horizontal grid and an adaptive vertical coordinate without the need to interpolate fluxes at the air-sea interface. Given that both FIM and iHYCOM are very different from the current North American Multi-Model Ensemble models, they will add diversity to multi-model ensembles, and will likely improve the overall skill of subseasonal prediction.

This work is viewed as a part of NOAA's effort to improve subseasonal forecast and a step toward seamless prediction covering the range from medium-range numerical weather prediction to annual time scales.

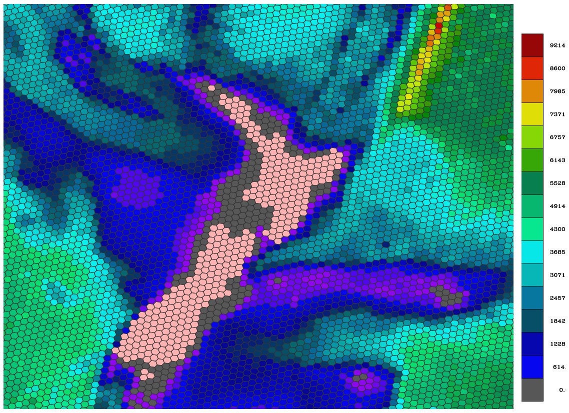

Figure 1: Sample figure showing land areas and ocean depth (m) on icosahedral grid at 30 km resolution.

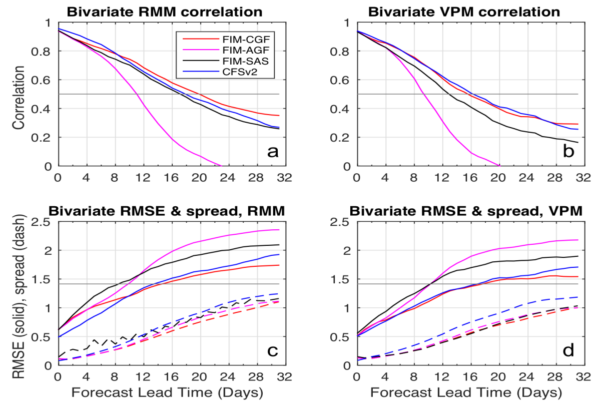

Figure 2: Model performance as a function of lead time for FIM-iHYCOM coupled GF and SAS (FIM-CGF and FIM-SAS, respectively), atmospheric only GF (FIM-AGF) and CFSv2 ensemble mean forecasts of the RMM (left) and VPM (right) indices. Top: Bivariate RMM correlation; Bottom: Bivariate root-mean-square error (solid) and 4-member ensemble spread (dashed).

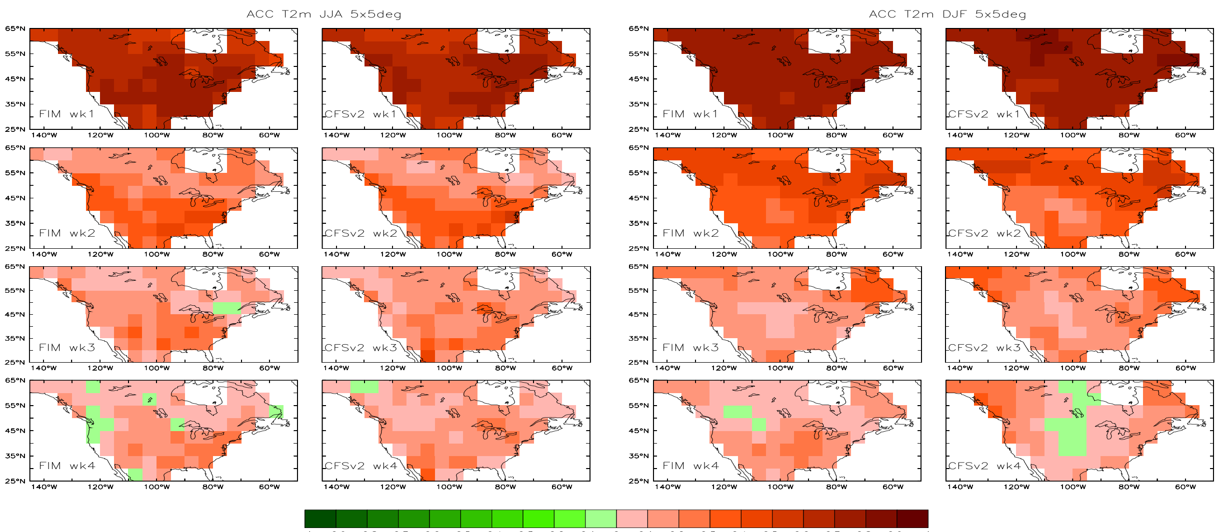

Figure 3: ACC for 2 m temperature in JJA (left) and DJF (right) from FIM-iHYCOM (FIM-CGF) and CFSv2 at different lead times. Data are averaged over 5°× 5° grid boxes.

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