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Sea Ice in the NCEP Forecast System

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Sea ice plays a significant role in global climate and weather, and affects and reflects global changes of the atmosphere and oceans. For this paper, we provide a summary of the sea ice processes represented in the NCEP Forecast System, which includes (1) sea ice observation used at NCEP; (2) sea ice in the NCEP mesoscale forecast system; (3) sea ice in the NCEP real-time ocean forecast system; (4) sea ice drift model at NCEP; (5) sea ice in the NCEP global forecast system; (6) sea ice in the NCEP climate forecast system; and (7) sea ice in the NCEP climate forecast system reanalysis.

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1. Sea Ice Observations

Sea ice models require a starting point, preferably, observational. The best-observed quantity is total sea ice concentration (fraction of an area that has some sea ice coverage). Sea ice thickness is observed locally from ships and planes, and by upward-looking sonar on submarines or moorings. At large scale, satellites observe sea ice thickness by laser or radar altimetry. The sea ice velocity field is also an important quantity, but is not well-observed in near real time. IABP (International Arctic Buoy Programme) buoys are sparse, and Arctic-only. And satellite observations lag real time. Fortunately, this variable, at least, is not crucial for forecasts, as ice equilibrates with its forcing within about 12 hours.

Sea ice concentration for NCEP models is derived from passive microwave observations (SSMI, SSMI-S, AMSR) using the NASA Team-1 (Cavalieri 1992), Team-2 (Markus and Cavalieri 2000), and NCEP regression against either. See Grumbine (1996) for the original operational implementation, and Grumbine (2014) for the history of operational systems since that time. The passive microwave observations provide daily, global coverage, at approximately 12 km resolution. This is not a limit for models such as the Global Forecast System (GFS), but is a factor for ice conditions in the mesoscale forecast system, with its 4 km grid spacing.

Climate reanalysis projects, including that which was involved in the Climate Forecast System (CFS) version 2 (Saha et al. 2014), require sea ice observations as well. Fields have been constructed for the NCEP/NCAR Reanalysis (one degree and half degree, (Kalnay et al. 1996)), the North American Regional Reanalysis (32 km, (Mesinger et al. 2006)), and the CFS Reanalysis (half degree, (Saha et al. 2010)).

2. Sea Ice in the NCEP Mesoscale Forecast System

In the mesoscale forecast system, the North American Model (NAM), sea ice is treated very simply. Ice does not move. When ice is present, it is 100% coverage, and 3 meters thick. This layer is treated essentially as land, and is part of the NOAH land surface model (Ek et al. 2003), with the main difference being the basal boundary condition, where ice temperature is fixed at 271.13 K (-2.02 C). A secondary difference is the depth layers at which temperatures are computed, which are equally spaced 0.75 m apart, as opposed to at depths of 0.1, 0.3, 0.6, and 1 meter in other portions of the model.

The initial conditions for ice cover are taken from the IMS (Interactive Multisensor Snow and Ice Mapping System) ice (Chen et al. 2012), due to the high resolution requirement of the NAM, and the fact that IMS's analysis is ice/no-ice, as are the physics of the NAM.

3. Sea Ice in the NCEP Real-Time Ocean Forecast System

As for the atmospheric GFS (in section 5), sea ice is assumed to not move. Further, it does not include ice concentration or thickness. The effects of sea ice on the ocean are retained only in their effect on air-sea heat exchange (no exchange if 'sea ice' is present) and on the atmospheric radiation in terms of albedo reflecting atmospheric radiation.

The 'sea ice' is not exactly sea ice, in that it has neither concentration nor thickness. Nor does it support a snow cover. It is an 'energy loan' model. If the ocean would be cooled below the freezing point by current air-sea heat fluxes, the ocean is kept at the freezing point, and a 'loan' is taken from an energy 'bank'. This energy loan must be repaid before the ocean is allowed to warm above the freezing point. The magnitude of the loan can be equated to a sea ice thickness by dividing by ice density and latent heat of fusion.

4. Sea Ice Drift Model at NCEP

The NCEP sea ice drift model is a virtual floe model. That is, it is assumed that there is an ice floe at each point in the domain, and the cumulative drift of this floe is then computed. This is useful to forecasters, as they will always have guidance on the ice motion, whether or not a more complete model thinks there is, or will be, ice in an area. The original model was implemented in the National Meteorological Center (NMC, NCEP's precursor) in 1978, for 2 day forecast guidance. The current version of the model (Grumbine 1998, 2013) provides guidance to 16 days.

The physics include no thermodynamics, and the dynamics are quite simple. Sea ice is assumed to drift at a fraction of the wind speed, and at an angle to it – an approach first suggested by Nansen (1902). What has changed over the years is exactly which wind is used (geostrophic winds 1978-2007, 10 meter winds 2007-present), and what fraction and angle are used to represent the sea ice's response to winds.

5. Sea Ice in the NCEP Global Forecast System

The sea ice model in the GFS was the version that was implemented on May 31, 2005, when NCEP implemented major changes to its GFS. The horizontal resolution increased from approximately 50 km (T254) to approximately 35km (T382) in both the analysis and forecast model for the four GFS cycles at 00, 06, 12, and 18 UTC. The vertical resolution, which had varied from 64 to 28 layers, became 64 layers for the entire 16-day forecast. Changes to the analysis consisted of additional radiance data, enhanced quality control, and improved emissivity calculations over snow and ice. Changes to the model consisted of new sea ice and land-surface models, modified vertical diffusion, and enhanced mountain blocking. (http://www.emc.ncep.noaa.gov/gc_wmb/Documentation//TPBoct05/T382.TPB.FINAL.htm)

The sea ice model was based on Winton's (2000) three-layer (two equally thick sea-ice layers and one snow layer) thermodynamic process. It predicts sea ice/snow thickness, surface temperature, and ice temperature structure. The surface temperature is determined from the diagnostic balance between the upward conductive heat flux through snow and/or ice and the upward heat flux from the surface (including short- and longwave radiation, and sensible and latent heat fluxes). The ice temperature (upper and lower layers) is calculated based on conservation of enthalpy. If the calculated surface temperature is greater than the freezing temperature of snow or sea ice (when there is no snow cover) the surface temperature is fixed at the melting temperature of snow or sea ice, and the ice temperature is recomputed. The residual energy flux is applied toward surface melting of snow or sea ice (if no snow). At the ice/water interface, the conservation of energy dictates that the energy absorbed or released through melting (or freezing) balances the oceanic heat flux to the ice bottom and the conductive flux of heat upward from the bottom. The analyzed fractional ice cover is kept unchanged for the entire forecast, but there is an option to use climatology for daily sea ice concentration. The old scheme simply used a fixed sea ice array, either 100% or 0% ice cover (based on analysis data with 50% ice fraction cutoff), similar to that in the NCEP mesoscale forecast system. For the new model, heat and moisture fluxes and albedo are treated separately for ice and open water in each grid box (Wu et al. 1997).

The horizontal resolution of the sea ice model is the same as that of the atmospheric model in the GFS. When the GFS was upgraded to T574 (approximately 27km) on July 27, 2010 the sea ice model resolution in the GFS was increased at the same time.

Two case studies from cycled data assimilation/forecast experiments for January and July 2004 showed satisfactory performance of the new forecast model with interactive sea ice. While good agreement in the anomaly correlation between the new and old models is observed from the GFS, the low-temperature bias in the lower troposphere in the high latitudes during winter has been greatly reduced in the new model (Wu et al. 2005), especially when a new data assimilation scheme is used (Okamoto et al. 2004) as shown in Fig. 1. For the summer season the cold bias is much smaller in the standard forecast and the reduction of the cold bias is thus less with an interactive sea ice model.

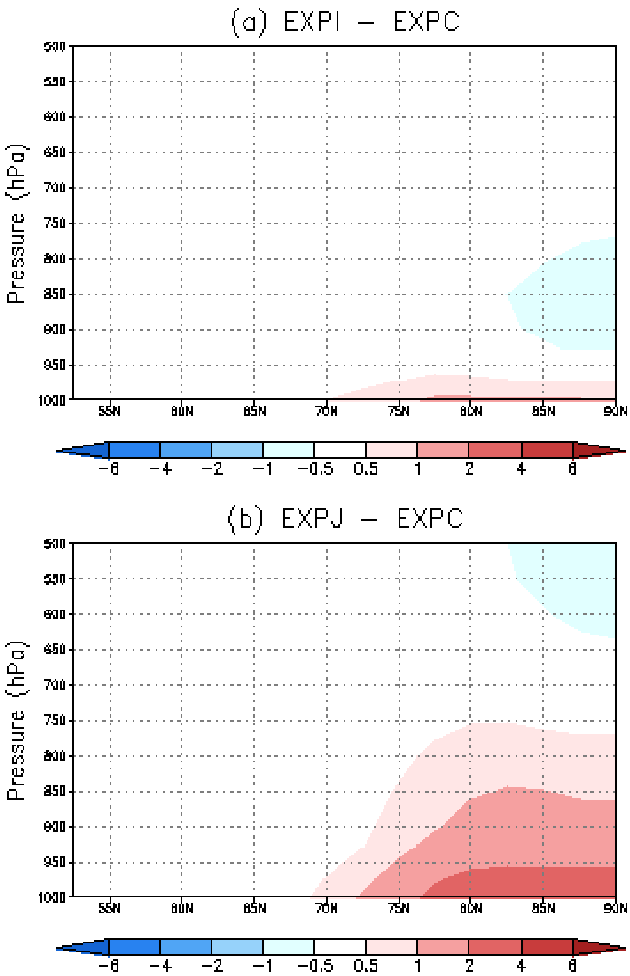

Figure 1. The zonal mean of the analyzed temperature difference in the GFS between (a) “EXPI” (EXPC plus a thermodynamic sea-ice model) and “EXPC” (Control Standard GFS) and (b) “EXPJ” (EXPI plus a new analysis scheme) and “EXPC” for January 2004.

6. Sea Ice in the NCEP Climate Forecast System

The current operation CFS is CFS version 2 (CFSv2). The model of CFSv2 is the NCEP coupled atmosphere-ocean-land surface-sea ice model. The atmospheric model is based on a previous NCEP operational GFS model with improvements including new radiation and physics (Saha et al 2014). The horizontal resolution is T126 for the forecast and T574 for the analysis, with 64 hybrid vertical layers in both cases. The ocean model is from GFDL Modular Ocean Model version 4p0d (MOM4, Griffies et al. 2004), with 40 vertical layers. The zonal resolution of MOM4 is 1/2^o. The meridional resolution is 1/4^o between 10^{o}S and 10^{o}N, gradually increasing through the tropics becoming 1/2^o poleward of 30^{o}S and 30^{o}N. The ocean model uses a tripolar grid north of 65^{o}N. The land surface model is the NOAH land surface model (Ek et al. 2003), which is imbedded in the GFS. The sea ice model is described below. Full details of the model description for the atmosphere, ocean, and land surface can be found in Saha et al. (2010, 2014).

The sea ice model is from GFDL Sea Ice Simulator with slight modifications. Similar to the ocean model, sea ice model components use a tripolar grid north of 65^{o}N, i.e., a grid that has "poles" located in the land masses of northern Canada and northern Russia, in addition to the normal South Pole. There are three layers for the sea ice model, including two equal layers of sea ice and one (optional) layer of snow with five categories of sea ice thickness (0-0.1, 0.1-0.3, 0.3-0.7,0.7-1.1, and the category greater than 1.1 m). The snow has no heat capacity, the upper ice layer has sensible and latent heat capacity (i.e. a variable temperature/salinity dependent), and the lower ice layer has only sensible (fixed) heat capacity. The base of ice is fixed at the (salinity dependent) seawater freezing temperature. Sea ice dynamics is based on Hunke and Dukowicz (1997) using the elastic-viscous-plastic technique to calculate ice internal stress. The ice strength follows that of Hibler (1979). Ice thermodynamics is based on Winton (2000). It is possible for ice to be transferred conservatively between the snow layer and the two ice layers when there is snowfall, evaporation, freezing, or melting. When sea ice forms over the ocean, it releases latent heat and salt to the ocean. Details can be found in Griffies et al. (2004).

The sea ice initial condition for the CFSv2 is from the CFS analysis system, which was the continuation of the CFS reanalysis (CFSR) system starting from 1979. Sea ice in the CFSR will be discussed in the next section.

Sea ice prediction is always challenging. Sea ice can form or melt, it can move with wind and/or ocean current. Sea ice interacts with both the air above and ocean underneath, it influences by, and has impact on the air and ocean conditions. Previous predictions of sea ice on seasonal time scales are based on statistical methods (e.g. Drobot et al. 2006, Lindsay et al. 2008) or using ocean-ice model with prescribe atmospheric forcing (e.g. Zhang et al. 2008). The CFSv2 with the sea ice component described above became operational in March 2011. One of the most important developments of CFSv2 compared to CFSv1 (CFS version 1) are the extension of the CFS domain for the ocean to the globe and incorporation of the sea ice component (Saha et al. 2014). Hindcast had been carried out for seasonal prediction with CFSv2, including the sea ice prediction. The prediction and reforecast of Arctic sea ice extent from CFSv2 has been assessed in details by Wang et al. (2013). Although the CFSv2 captured the observed seasonal cycle, long-term trend and interannual variability to some extent, large errors exist in its representation of the observed mean state and anomalies.

As there is no sea ice thickness data available for assimilation (Wu and Grumbine 2012, 2013), the bias of sea ice thickness in the model is crucial for sea ice prediction. In the CFSv2 the systematic bias caused sea ice to be thick in the initial condition, there is much sea ice left for the prediction, too thick and extensive. The model shows a consistent high bias in its forecasts of January-September ice extent without bias correction (Wang et al. 2013). One method of bias correction is to subtract the bias extent observed from the prediction in the reforecast. The second is to consider the model's bias as being excessive thickness, and then find the thickness greater than which the extent would match that observed. Both methods provided improved sea ice prediction for the minimum Arctic sea ice extent for 2010-2013. For example, when participated in the sea ice outlook organized by SEARCH (Study of Environmental Arctic Change), the prediction of the September sea ice with 24 ensembles for 2010 with 9-month lead time, leads to an estimate of 5.1 million km^2. When April 2010 initial condition with bias correction is used the prediction hits the target of 4.6 km^2 (http://www.arcus.org/search/seaiceoutlook/2010/august). However, for the case of 2012 when the Arctic sea ice hits its record minimum CFSv2 failed to predict the low amount in line with other models (http://www.arcus.org/search/seaiceoutlook/2012/august). One can argue that the predicted Arctic sea ice extent with bias for 2011-2013 is due to deficiencies in each component of the coupled CFS model and their interactions, and the initial state of the sea ice thickness. Our limited understanding of the coupled and complex interactions among atmosphere, ocean, land and sea ice, also hinders our ability (National Research Council 2012). The prediction of sea ice concentration for September 2014 is shown in Fig. 2.

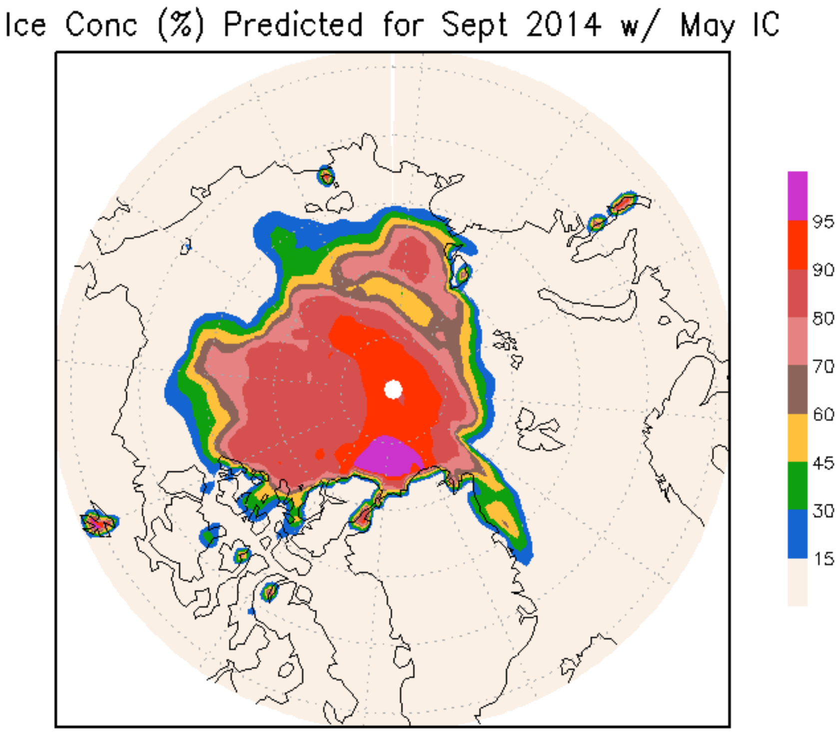

Figure 2. Sea ice concentration predicted for September 2014 in CFSv2 with 31 ensembles using May 2014 initial conditions (with bias correction for sea ice thickness). The sea ice extent based on the mean sea ice concentration is 5.3 million square kilometers.

7. Sea Ice in the NCEP Climate Forecast System Reanalysis

Sea ice is known to play a significant role in the global climate system. Realistic representation of sea ice is essential for good performance of atmospheric and oceanic data assimilation models over the polar regions in the CFSR. Global climate modeling studies show that sea ice concentration has a strong impact on the climate over the Antarctic regions (e.g., Simmonds and Budd 1991). Recent studies (e.g., Overland and Wang 2010, Screen and Simmonds 2010; Liu et al. 2012) demonstrate that the declining Arctic sea ice has a significant impact on the atmospheric circulation, surface latent heat flux and winter snowfall. We note that, there was no sea ice concentration in the previous NCEP reanalysis, the NCEP/NCAR Reanalysis-1 (R1) and NCEP-DOE Reanalysis-2 (R2), although sea ice concentration data from analysis were used to present the sea ice coverage in R1 and R2 with 55% cutoff (i.e. when sea ice concentration is greater than 55% it is considered as 100% sea ice coverage). The new CFSR at NCEP (Saha et al. 2010) allows us to add sea ice concentration from analysis into the reanalysis system, which leads to more realistic interactions between sea ice and atmosphere in the polar region. Detailed description of the sea ice data used in the CFSR, how sea ice concentration is assimilated, and the discussion of the implications for improvement in the products of the CFSR can be found in Saha et al. (2010), and Wu and Grumbine (2012, 2013).

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