SEA ICE PREDICTION NETWORK (SIPN)
Template for Pan-Arctic Sea Ice Outlook Core Contributions
July 2015 Report

*REQUIRED

1. *Contributor Name(s)/Group – how you would like your contribution to be labeled in the report (e.g., Wiggins et al.) Yuan et al., LDEO/Columbia University

2. * Individuals submitting "public" contributions should self-identify here:___x___ Yes, this is a "public" contribution.

3. *"Executive summary" about your Outlook contribution (max 300 words)
Say in a few sentences what your Outlook contribution is and why. To the extent possible, use non-technical language. The prediction is made by statistical models, which are capable to predict Arctic sea ice concentrations at grid points 3-month in advance with reasonable skills. The models employ 34 years of monthly time series of sea ice, SST and atmospheric variables. The pan Arctic SIE calculated from predicted ice concentration in September 2015 is projected to be 5.08 million square kilometers, lower than the observed extents in 2013 and 2014, but still above the historical low in 2012. The ice concentration is significantly below the 34-year climatology in the Beaufort Sea, Chukchi Sea, East Siberian Sea, Laptev Sea, Kara Sea and Barents Sea.

4. *Type of Outlook projection
___dynamic model __x_statistical ___heuristic ____mixed or other: (specify)

If you use a model, please specify:
Model Name __Linear Markov Models___________________________________
Components of the model: Atmosphere_x_, Ocean_x_, Ice_x_, Land__,
For models lacking an atmosphere or ocean, please describe the forcing: ___

5. *September monthly average projection (extent in million square kilometers. To be consistent with the validating sea ice extent index from NSIDC, if possible please first compute the average concentration for the month and then compute the extent as the sum of area of all cells > 15%.) 5.08 million square kilometers.

6. *Short explanation of Outlook method (max 300 words)
In addition, we encourage you to submit a more detailed Outlook, including discussions of uncertainties/probabilities, including any relevant figures, imagery, and references.
If this is a model contribution, please include method of method of initialization and variable used. A linear Markov model was used to predict monthly Arctic sea ice

concentration at all grid points in the pan Arctic region. The model is a stochastic linear inverse model that was built in the multivariate EOF (mEOF) space and is capable of capturing the co-variability in the ocean-sea ice-atmosphere system. The model employs 6 variables (NASA Team sea ice concentration, sea surface temperature (ERSST), surface air temperature, 300mb height and wind vectors at 300mb from NCEP/DOE reanalysis II) and 11 mEOF modes. In addition, we also used a regional Markov model for the Pacific sector of the Arctic, which provides better skills than the pan Arctic model in this region. The regional model was developed in a rotated mEOF space with three variables (sea ice concentration, sea surface temperature and surface air temperature) and 23 modes. The results from the regional model then replaced the predictions from the pan Arctic model in the Pacific region. The merged predictions of sea ice concentration from these two Markov models were used to calculate September SIE prediction and used for predictive skill assessments.

7. Projection uncertainty/probability estimate for September extent (only required if available with the method you are using) The uncertainty is measured by RMS errors (RMSE) between predicted and observed extents. EMSE for 3-month lead September sea ice extent predictions is 0.506 million square kilometers and the model skill measured by a correlation is 0.84.

8. Short explanation/assessment of basis for the uncertainty estimate in #6 (1-2 sentences) The uncertainty is estimated based on the cross-validated model experiments for three-month lead predictions of September ice concentration and sea ice extent using 34 years (1979-2012) of time series. The data used include SIC with the NASA Team algorithm, NCEP/DOE reanalysis II atmospheric variables and ERSST.

9. Please indicate if this contribution should be used for both the July 2015 and the August 2015 SIO reports:
   _____Yes, use this contribution for both July and August.
   ___x_No, a separate contribution will be submitted for the August report.

Predictions of September 2015 Arctic Sea Ice Based on June Observations

Xiaojun Yuan, Cuihua Li, Lei Wang, Michael Tippet, Mingfang Ting and Haibo Liu

Prediction models: Linear Markov models for Seasonal Predictions of Arctic Sea Ice Concentration (Yuan et al., submitted, Li et al., submitted) and Vector Auto-regressive model for the first ice-free day predictions.

Pan-Arctic Sea Ice Extent (SIE) Prediction: Based on the observations of sea ice concentrations (NASA Team Algorithm), SST (ERSST) and atmospheric variables (NCEP/NCAR reanalysis) in June, the models predict that the Pac-Arctic Sea Ice Extent (SIE) will be 5.08 million square kilometers.

Regional Sea Ice Concentration Prediction: Predicted September sea ice concentration anomalies and concentrations at grid point are displayed in figure 1. The negative anomalies of ice concentration are larger than 40% from the Beaufort Sea to the Laptev Sea. The concentration anomalies are relative to the climatology of 1979-2012.

Method: A linear Markov model has been developed to predict the ice concentration in the pan Arctic region at the seasonal time scale, which represents an original effort of forecasting Arctic sea ice year around with a reduced-dimension statistical model (Yuan et al, in revision, Chen and Yuan, 2004). The model was built to capture co-variabilities in the atmosphere-ocean-sea ice system defined by sea ice concentration, sea surface and air temperature, geopotential height and winds at the 300mb level. Multivariate empirical orthogonal functions (mEOF) of these variables served as building blocks of the model. A series of model experiments were carried out to determine the dimensions of the model. Based on these experiments, we selected the first 11 mEOF modes to construct the model. A linear Markov process predicted principle components of these modes, one month at a time. The predicted principle components were then combined with corresponding eigenvectors to produce the final prediction (Yuan et al., in revision). To enhance the prediction in the Pacific sector of the Arctic, a similar linear Markov model was developed for the Pacific sector of the Arctic (40°-84°N, 120°W-120°E), which focuses on the regional dominant coupled relationships. The regional model significantly improves the season forecast skills in the region, compared to the pan Arctic model (Li et al., submitted). Both pan Arctic and Pacific regional models were developed using 34 years (1979-2012) of NASA team sea ice concentration, ERSST and NCEP/DOE reanalysis II atmospheric variables. The 3-month lead prediction of September sea ice concentration is produced by replacing the predictions from the pan Arctic model with that from the regional model in the Pacific sector of the Arctic (figure 1). The predictive skills of these models were evaluated in a cross-validated fashion, which is measured by anomaly corrections between predicted and observed ice concentration anomalies. The models show considerable skills within the Arctic Basin at the end of summer (figure 2). Particularly, predictive skills for September forecast at 3-month lead are above 0.6 in the Beaufort Sea, Eastern Siberian Sea and Laptev Sea, and the maximum skill reaches 0.95 north of the Chukchi Sea. The skill of predicting the September Arctic SIE is 0.84 at the 3-month lead-time. Regional ice extents are also calculated and presented in figure 3.

Moreover, the probability of sea ice concentration higher than 15% is produced at each grid point by the method of logistic regression (Hamill and Whitaker, 2006) and is presented in figure 4.

In addition, we develop a statistical model for predicting ice-melting date using daily sea ice concentration data. The daily ice concentration is predicted for the period of July 1st (Julian day 183) to September 30th (Julian day 273), 2015 using a Vector Auto-Regressive (VAR) model (Wang et al., submitted). The VAR model uses sea ice concentration as the only predictor and is trained with the 1979-2014 July to September (JAS) daily data. For each day in the forecast period, the prediction is made directly from the June 30th, 2015 data (i.e., by leaping instead of integrating iteratively). The ice-melting date is defined when predicted ice concentration is below 15% and stays below 15% for next 7 days (Stammerjohn et al., 2008). Predicted ice-melting date in 2015 is shown in Figure 5a. Any location where concentration stays above 15% until September 30th is given the ice melting date of 274 (the grey regions around the North Pole in Figure 5a), implying that ice will not melt below 15% in 2015. The take-one-year-out cross-validation is used to estimate the root-mean-square-error (RMSE) in the melting date predictions (Figure 5b).

Uncertainty: The uncertainty of the September Arctic SIE prediction, measured by RMSE, is 0.506 million square kilometers. The uncertainties of sea ice concentration predictions, also measured by RMSE, are shown in figure 2b. Larger RMSE occurs in the marginal seas within the Arctic Basin, where RMSE ranges 20% to 30%. These uncertainties are based on cross-validated experiments using 34-year observations. The RMSE for the ice-melting date prediction is at a range of 10-20 days in most the Arctic Basin. In scattered locations, the RMSE of the melting date prediction can be as large as 30days.

Executive summary: The three-month lead September Arctic sea ice predictions include predictions of monthly mean sea ice concentration, the pan Arctic sea ice extent, regional ice extents, Arctic sea ice probability, and prediction of the sea ice melting date. The sea ice concentration prediction is made by linear Markov models, which are capable to predict Arctic sea ice concentrations at grid points 3-month in advance with reasonable skills. The pan Arctic SIE calculated from predicted ice concentrations in September 2015 is projected to be 5.08 million square kilometers, lower than the observed in 2013 and 2014, but still above the historical low in 2012. The ice concentration is significantly below the 34-year climatology in the Beaufort Sea, Chukchi Sea, East Siberian Sea, Laptev Sea, and Kara Sea.

References:

Chen, D. and X. Yuan, 2004: A Markov model for seasonal forecast of Antarctic sea ice. *Journal of Climate,* 17(16), 3156-3168.

Li, Y., X. Yuan, D. Chen, Q. Zhang, C. Li, F. Niu. and Y. Sun, A Regional Model for Seasonal Sea Ice Prediction in the Pacific Sector of the Arctic. Submitted to *JGR-Atmospheres*.

Hamill, T. M. and J. S. Whitaker, 2006: Probabilistic Quantitative Prediction Forecasts Based on Reforecast Analogs: Theory and Application. *Monthly Weather Review*, 134, 3209-3229.

Stammerjohn, S. E., D. G. Martinson, R. C. Smith, X. Yuan, and D. Rind, 2008: Trends in Antarctic annual sea ice retreat and advance and their relation to El Niño–Southern Oscillation and Southern Annular Mode variability. *J. Geophys. Res.*, **113**, C03S90, doi:10.1029/2007JC004269.
Yuan, X., D. Chen, C. Li and L. Wang, Arctic Sea Ice Seasonal Prediction by a Linear Markov Model. In revision.
Wang, L., X. Yuan, M. Ting, and C. Li. Predicting Summer Arctic Sea Ice Intra-Seasonal Variability Using a Vector Auto-Regressive Model. Submitted to *J. Climate*.

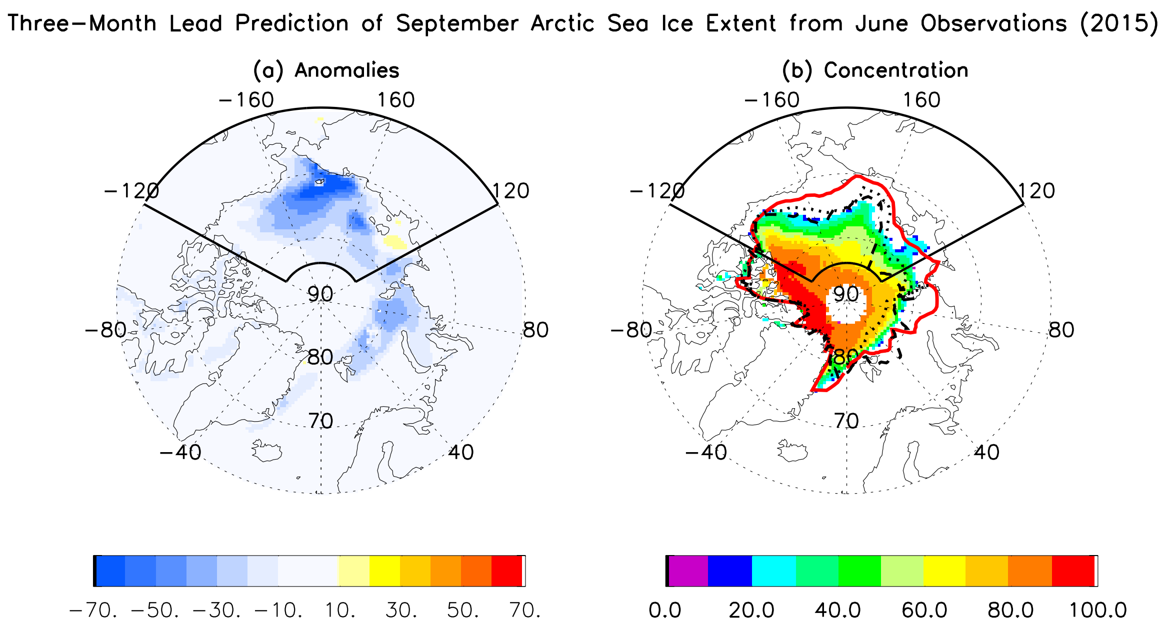

Figure 1. Three-month lead Prediction of September Sea ice concentration anomalies (a) and concentration (b) by the linear Markov models, initialized with June observations of SIC, SST and geopotential heights and winds at 300mb surface. The units are in percentage in both (a) and (b). The results in the region between 120°W and 120°E and south of 84°N are derived from the Pacific regional Markov model and the results in the rest areas are from the pan Arctic Markov model. Red contour in (b) indicates climatological (1979-2012) ice edge, and dotted (dashed) black lines represent ice edge in 2013 (2014), respectively.

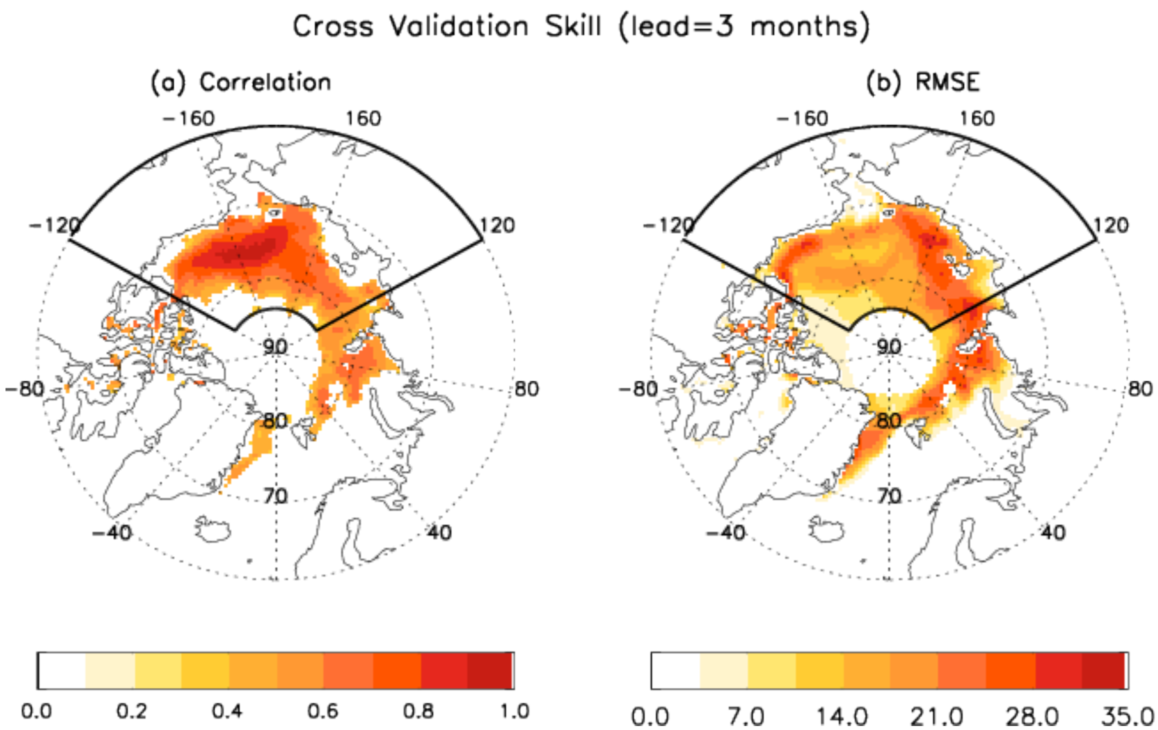

Figure 2. Cross-validated model skills measured by correlations between model predictions and observations of Arctic sea ice concentration anomalies (a) and model RMSE (b) for three-month lead prediction of September sea ice concentration. Only the correlations that pass the 95% confidence level are shown in (a). The units in (b) are in percentages. The low correlations and low RMSE near the North Pole Hole (the satellite blind spot) are due to low ice variability. The results in the region marked by black lines are derived from the Pacific regional Markov model, and the results in the rest areas are from the pan Arctic Markov model.

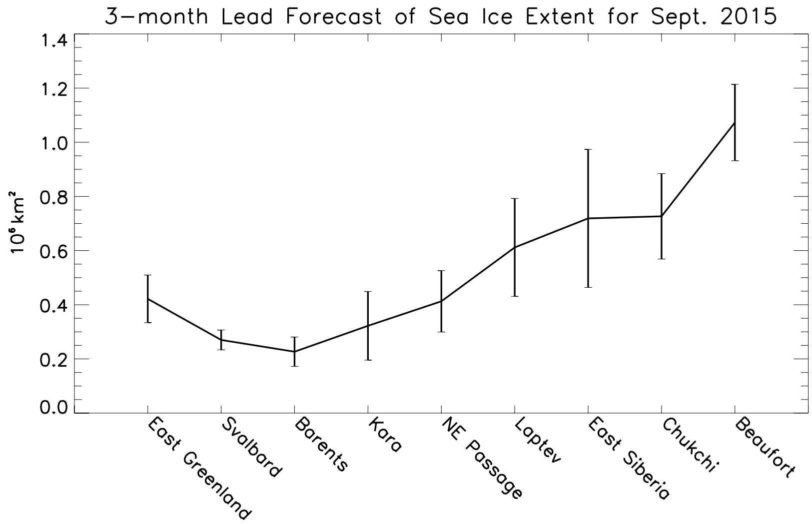

Figure 3. Regional sea ice extents in unit of million square kilometers for September 2015.

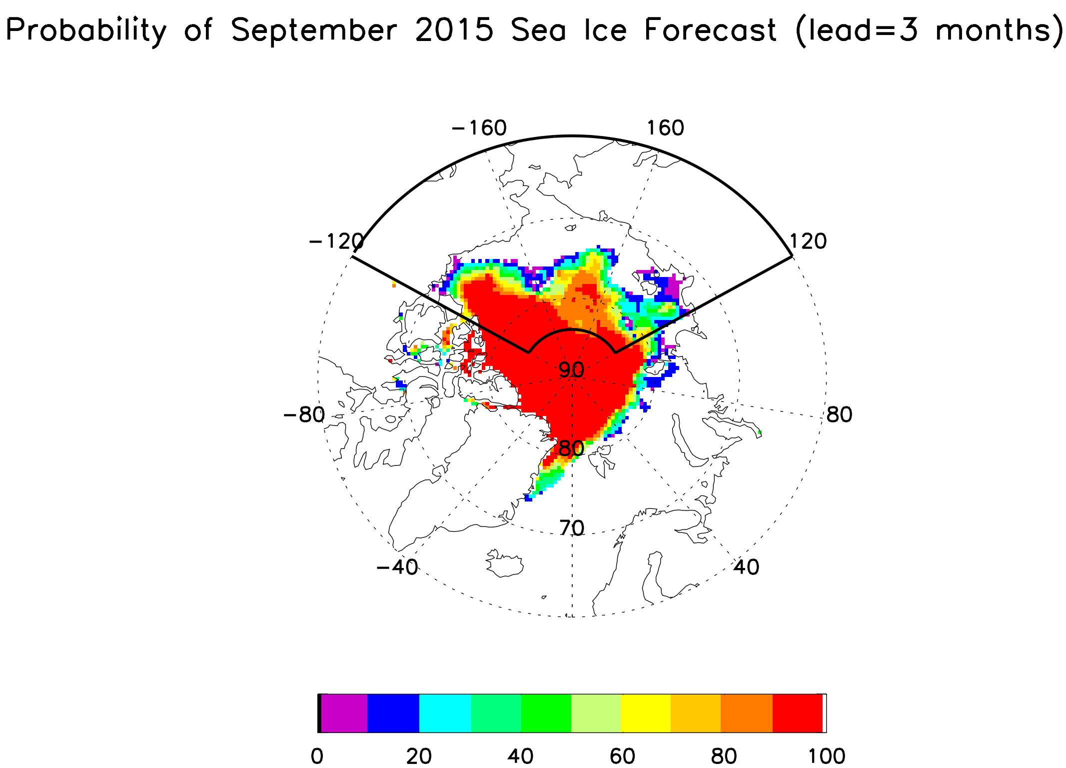

Figure 4. Sea ice probability in September 2015 based on combined Markov models predictions of sea ice concentrations.

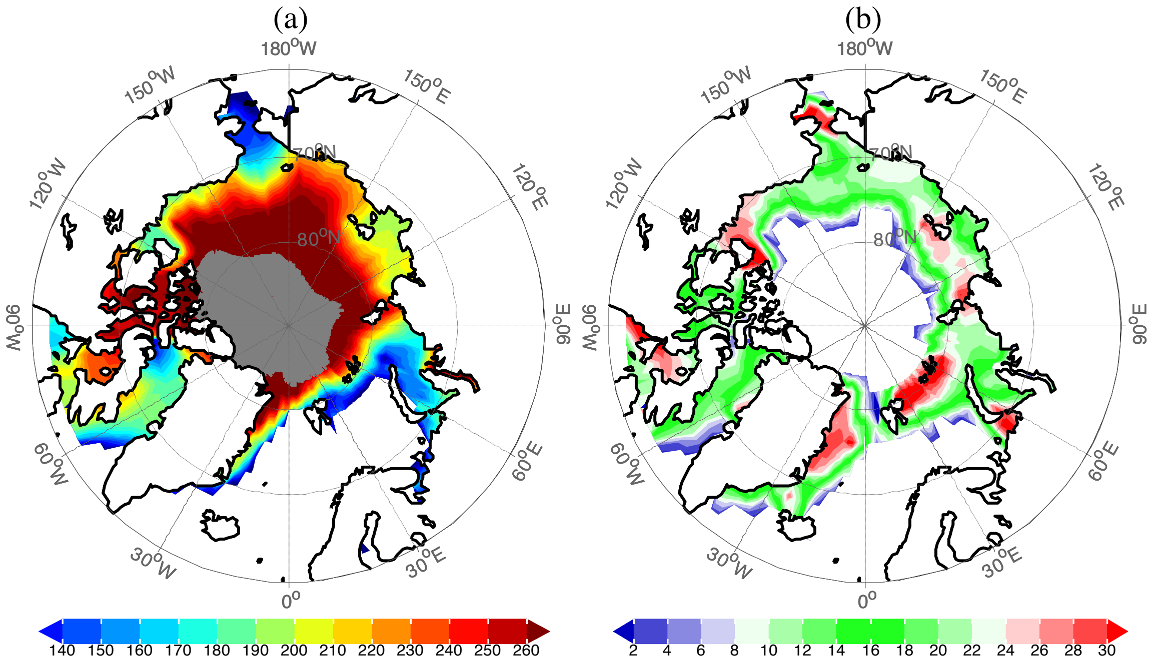

Figure 5. (a) Ice-melting date in the Julian day, e.g., 152/182/213/244/274 corresponds to Jun./Jul./Aug./Sep./Oct. 1st, 2015, respectively. The grey shading indicates the regions where the sea ice concentration stays above 15% until Sep. 30, 2015. (b) RMSE of the first ice-free day predictions based on 1979-2014 cross-validations.