AIMdyn, Inc.
Engineering Consulting & Software Development

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Contract: **N00014-18-P-2004** **Date: 05/30/2018**

Project Title: Analysis and Prediction of Sea Ice Evolution using Koopman Mode Decomposition Techniques

Subject: Monthly Progress Report

Period of Performance: May 1, 2018 – May 30, 2018

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AIMdyn, Inc. respectfully submits Progress Report 2 for contract N00014-18-P-2004. Please direct any Technical questions on this report to the undersigned.
V/r

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Business Status Report

(1) Resource Status:
Resourced to plan.

(2) Contributions by AIMdyn Inc:
See technical report.

(3) Resource status VS Original schedule:
On plan to original scope of work. Effort is fixed priced.

PROGRAM FINANCIAL STATUS

Work Breakdown	Cumulative to Date	At Completion
CLIN#0001-CLIN#0002	$37,374	$112,125

Structure or Task Element	Planned Expend	Actual Expend	% Budget Compl	At Compl	Latest Revised Estimate	Remark Remark
CLIN#0002	$18,687	$18,687	33.3%	100 %	N/A	N/A

Subtotal: $18,687
Management Reserve: N/A
Or Unallocated Resources: N/A
TOTAL: $18,687

Technical Status Report

Abstract

Koopman Mode Analysis was newly applied to southern hemisphere sea ice concentration data. The resulting Koopman modes from analysis of both the southern and northern hemisphere sea ice concentration data shows geographical regions where sea ice coverage has decreased over multiyear time scales.

ACCOMPLISHMENTS

Summary

The data processing techniques developed in the previous month for northern hemisphere data were applied to southern hemisphere data and showed similar results. The spatial modes corresponding to eigenvalues of interest were examined to show the geographic significance of sea ice concentration variations.

Introduction

Work in the second month consisted of applying the windowed time range Koopman mode analysis techniques to southern hemisphere sea ice concentration data and comparison of those results with those for the northern hemisphere, and examination of the Koopman modes corresponding to the Koopman eigenvalues identified as being of interest. For each related eigenvalue and mode, the eigenvalue determines the time dependent behavior of the mode and the mode determines the spatial significance of the specific dynamical behavior given by the eigenvalue. In this case, examination of a mode shows us the geographic locations where sea ice concentration is changing and the related eigenvalue tells us how the concentration in those locations changes over time.

Methods

The windowed Koopman mode analysis technique was applied to monthly antarctic sea ice concentration from the NSIDC Sea Ice Index. This data was available for the same time range (1979 to 2017) as for the northern hemisphere. This data set was missing data for several months (December 1987 and January 1988), so the missing data was replaced by interpolation between existing data points. The Koopman eigenvalues and modes were found to be the same for different Koopman algorithms, so the Arnoldi algorithm was used exclusively for the following results. For the windowed analysis, five year windows were believed to be the most meaningful so the following results are for five year windows. Also shown are results from the full 39 year period.

The time dependence of a Koopman mode depends on the corresponding eigenvalue's real and imaginary components; the real component determines the growth or decay behavior, while the imaginary component determines the oscillatory behavior. To identify multiyear trends, the eigenvalues with oscillation periods longer than one year (i.e. small imaginary components) were selected and their related modes examined to see the geographic regions that experience the identified time dependent changes in sea ice concentration. The growth or decay behavior (determined by the real component) is also important in understanding the multiyear change in sea ice concentration, as a small (more negative) value implies a rapidly decaying trend, which if sufficiently fast is unlikely to be of long-term importance, while a larger (less negative) value corresponds to more gradual decay that can be of significance over multi-year time scales. Note that no eigenvalues with positive real components were found, consistent with the observed trend of decreasing sea ice concentration over time. The geographic information revealed in the modes was of interest to localize regions where sea ice thickness is changing the most.

Results and Discussion

The eigenvalues for the five-year windowed analysis applied to the southern hemisphere sea ice concentration data show similar trends as the north hemisphere data. In Figure 1, it is seen that beginning in the 1990's, there is often one or more eigenvalues with imaginary values near zero and close to the origin, representing slowly decaying behavior (i.e. decreasing sea ice concentration). The spectrograph of the same eigenvalues (Figure 2) shows the expected peak at a period of one year (representing the annual sea ice variation), with generally increasing amplitude over time, representing a relatively greater annual variation in sea ice concentration.

As described above, the Koopman modes show the spatial significance of the dynamical behavior described by the eigenvalues. Figure 3 shows modes corresponding to the mean and annual variation in sea ice concentration for the southern hemisphere for the five year windows from 1979-1983 and 2013-2017. It is clear that the mean sea ice concentration is less in the later time period, suggesting that the sea ice does not reach as great an extent in the winter, and the annual variation occurs over a larger region closer to Antarctica, suggests a year-to-year reduction in summer sea ice coverage near the continent, particularly near West Antactica. Similarly, Figure 4 shows the modes corresponding to the mean and annual variation for sea ice concentration in the northern hemisphere for the two different year periods. The same decrease in mean sea ice coverage and increase in the region undergoing significant annual variation is observed. Such changes are especially apparent in the regions of the Beaufort Sea north of Alaska and the Kara Sea north of Russia.

Analysis of the entire 39 year period covered by the data shows similar results as obtained from comparing the early and later five year periods. Figure 5 shows a mode with slow decay and long oscillation period representing a decrease in sea ice concentration in the southern hemisphere, primarily consisting of a decrease in sea ice concentration in West Antarctica. This region is known to be warming more rapidly than the region as a whole, so this KMD mode is consistent with that observation and the result from the five year windows above showing decreased mean ice coverage and increased annual variation near West Antarctica. Figure 6 shows a number of similar modes from the northern hemisphere for the entire 39 year data set with slowly decaying and, in some cases, slowly oscillating time dependence. These modes show that the decrease in sea ice coverage is most pronounced in the regions of the Beaufort Sea and the Arctic Ocean north of European Russia, consistent with the

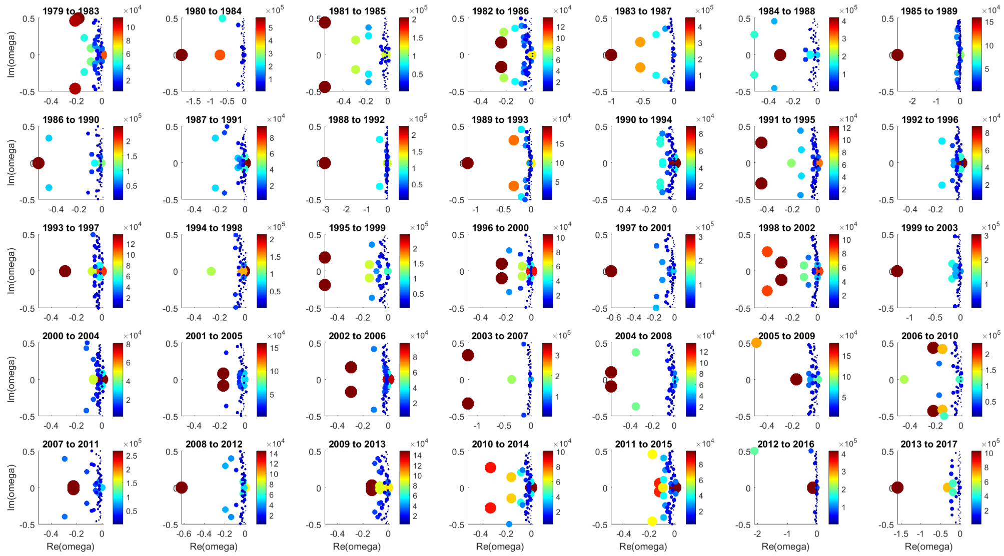


Figure 1: Koopman eigenvalues for 5 year time windows begining in 1979. Each circle corresponds to the eigenvalue of a Koopman mode, where the size and color of the circle are both representations of the L2 norm of the corresponding mode, the position along the horizontal axis shows the growth or decay constant of the mode (e.g. the more negative the value the faster the mode decays), and the position along the vertical axis shows the oscillatory frequency of the mode. The time scale is in months, so the two circles generally visible at approximately ± 0.08 on the vertical axis are the expected annual variation of the sea ice concentration. The novel result apparent is the mostly consistent presence of a large norm mode near the origin beginning in the 1990's.

changes in the mean and annual variation oberved in the five year window cases above.

Conclusions

The results obtained in this month show the consistency of the Koopman analysis technique as applied to sea ice concentration data from the northern and southern hemispheres, as well as the ability of the analysis to identify geographic regions undergoing long-term decreases in sea ice concentration.

Future work is planned to include analysis of sea ice thickness data using these techniques.

Personnel Supported

Dr. Maria Fonoberova, Dr. Igor Mezic, Dr. James Hogg

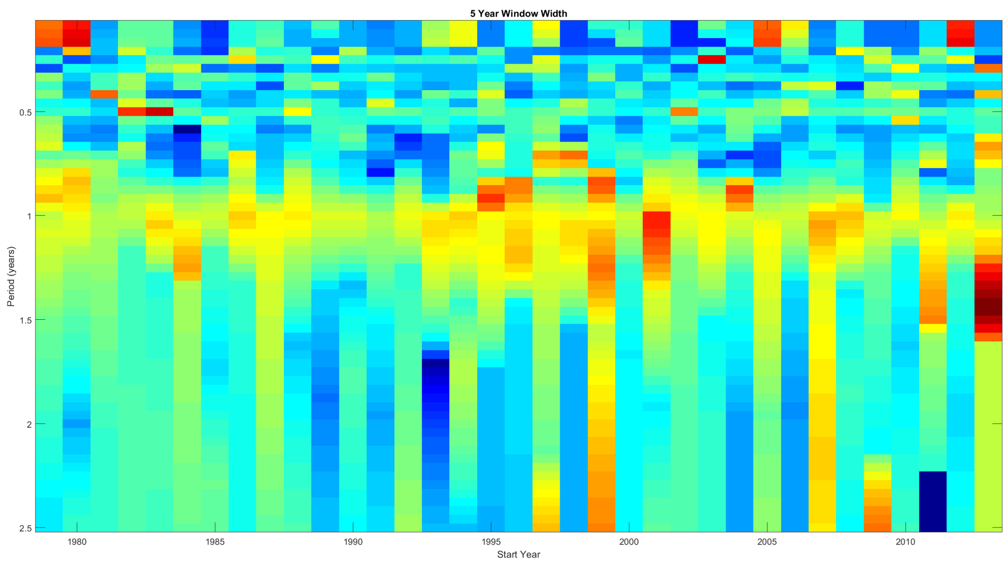
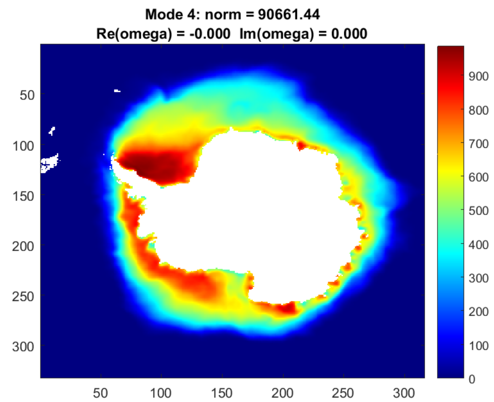
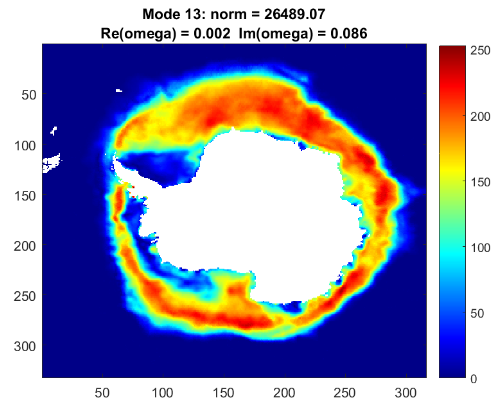


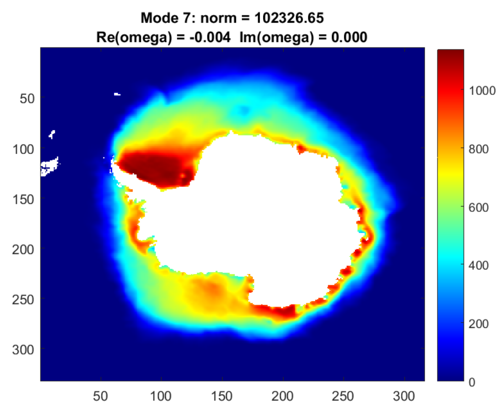
Figure 2: Koopman spectrograph showing period (in years) of eigenvalues. The consistent peak at one year represents the annual variation in sea ice concentration.



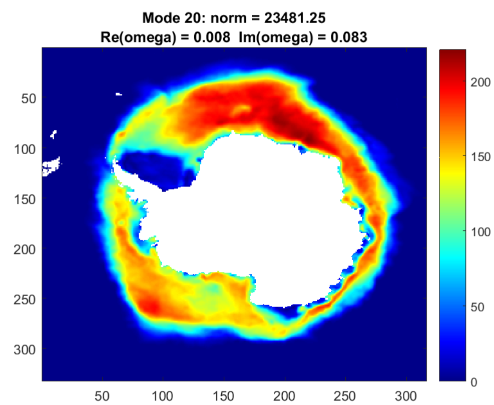
(a) Mean mode, 1979-1983.



(b) Annual variation mode, 1979-1983.

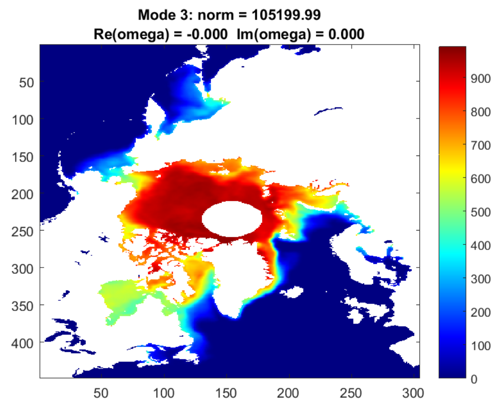


(c) Mean mode, 2013-2017.

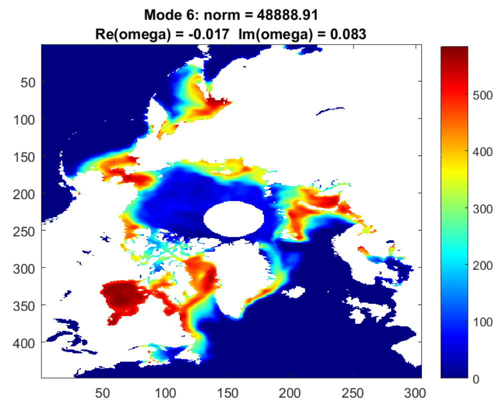


(d) Annual variation mode, 2013-2017.

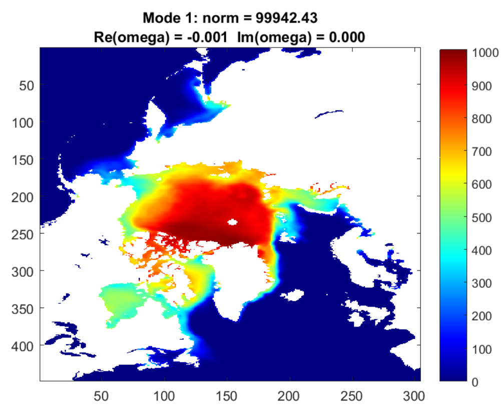
Figure 3: Koopman modes representing the mean and annual variation in sea ice concentration over five year windows for the southern hemisphere. (a) Mean coverage, 1979-1983 period, (b) annual variation, 1979-1983 period, (c) mean coverage, 2013-2017 period, (d) annual variation, 2013-2017 period. A general decrease in sea ice coverage is apparent, particularly near West Antarctica.



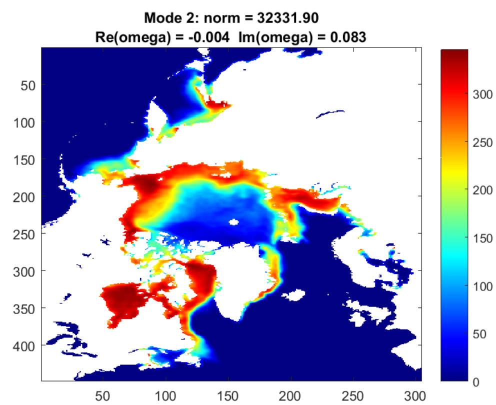
(a) Mean mode, 1979-1983.



(b) Annual variation mode, 1979-1983.



(c) Mean mode, 2013-2017.



(d) Annual variation mode, 2013-2017.

Figure 4: Koopman modes representing the mean and annual variation in sea ice concentration over five year windows for the northern hemisphere. (a) Mean coverage, 1979-1983 period, (b) annual variation, 1979-1983 period, (c) mean coverage, 2013-2017 period, (d) annual variation, 2013-2017 period. A general decrease in sea ice coverage is apparent, particularly in the Beaufort and Kara seas.

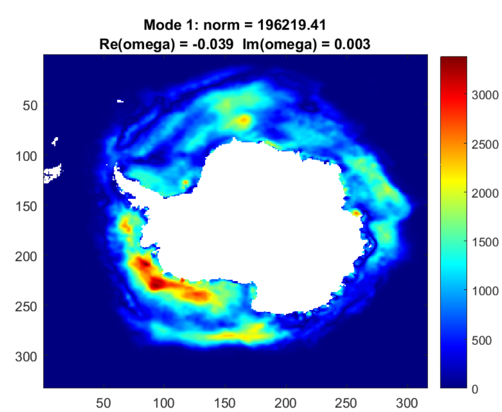


Figure 5: Mode from entire 39 year data set showing long term decrease in sea ice off West Antarctica.

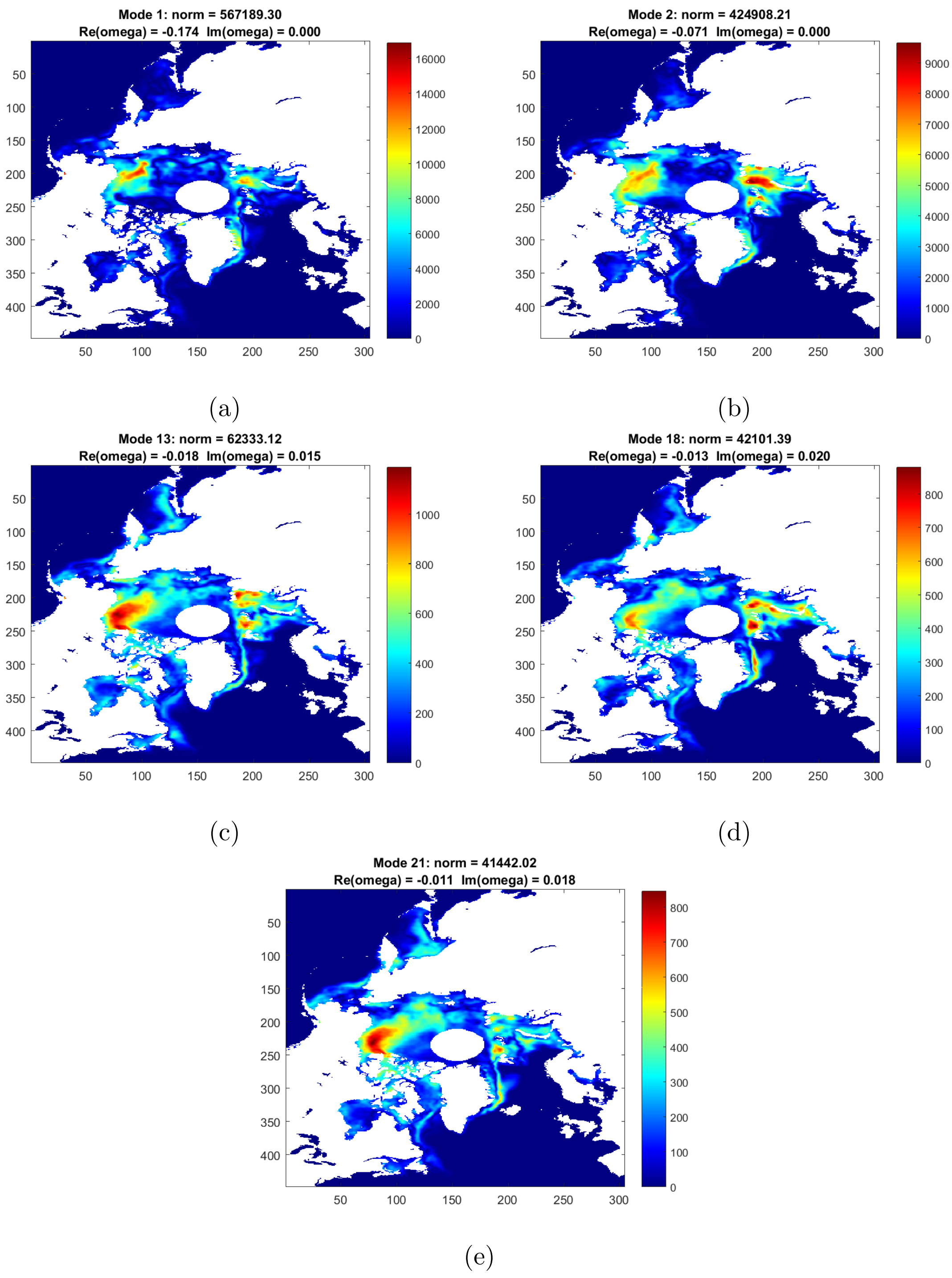


Figure 6: Modes from entire 39 year data set for the northern hemisphere, showing long term decrease in sea ice north of Alaska and European Russia.