THE RISE AND FALL OF EL NINOS AND THEIR IMPACT ON CARBON SEQUESTRATION IN THE NORTH PACIFIC OCEAN

Joaquim I. Goes[1], Helga do R. Gomes[1], Atsamon Limsakul[2] and Toshiro Saino[3,4]

1 Bigelow Laboratory for Ocean Sciences, 180 McKown Point Road, West Boothbay Harbor, Maine 04575, USA

2Environmental Research and Training Center, Technopolis, Pathumthani 12120, Thailand

3 Institute of Hydrospheric and Atmospheric Sciences, Nagoya University, Nagoya 464-8601, Japan

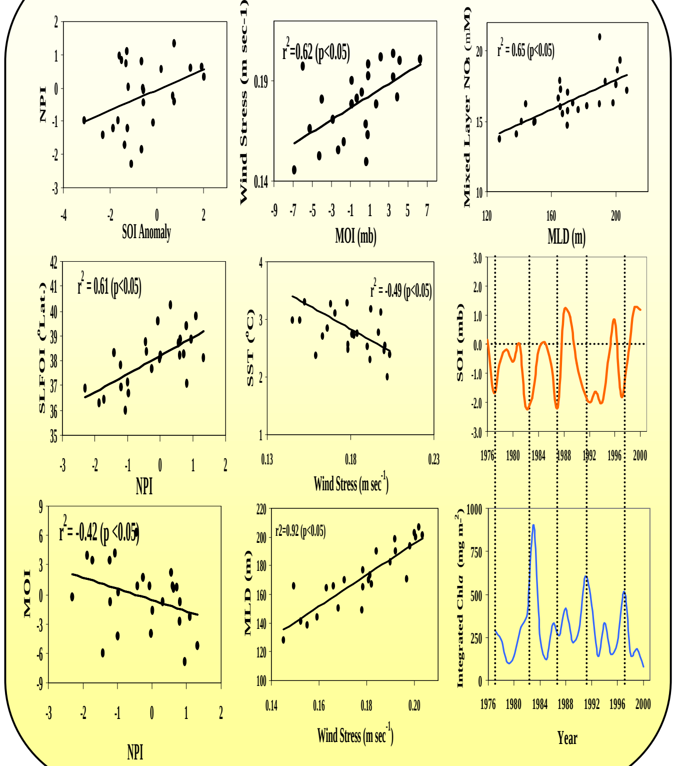
4Frontier Research System for Global Change, 3173-25, Yokohama 236-0001, Japan

ABSTRACT

The subarctic Pacific Ocean experiences strong climate-modulated seasonal, interannual to decadal variations in meteorological and physical oceanographic conditions, which can have a profound influence on biological processes and carbon cycling in the region. A satellite database beginning from 1997 provided us with evidence of strong interannual variations in the supply of inorganic nitrate and new production in the subarctic Pacific in association with the El Niño event of 1997. Although this data allowed us to view and describe large changes in new production along the entire breadth of the subarctic Pacific basin, our accessibility to a 25-year database of shipboard measurements enabled us to better focus on the western subarctic Pacific. Thus, in addition to the primary motive of corroborating our results from satellites, this exercise allowed us to obtain a clearer picture of the mechanistic connections between the atmosphere and the oceans, and the biological response to these changes. The results from this study make a compelling case that the primary driver for interannual variations in biological production in the western subarctic Pacific is the strength of the wintertime monsoonal winds. These winds can be particularly strong during El Niño years, when the Aleutian Low intensifies and moves southeastwards. During this period oceanographic conditions undergo several changes as is evident in the satellite and shipboard data. These changes in tandem, contribute to an increase in the supply of nutrients as well as an increase in the overall area of the North Pacific coming under influence of high nutrients. Unusually calm springs that follow these windy winters provide water column stability required for phytoplankton to benefit from the availability of nutrients. Both the satellite and shipboard showed how these conditions were reversed following the transition to La Nina conditions.

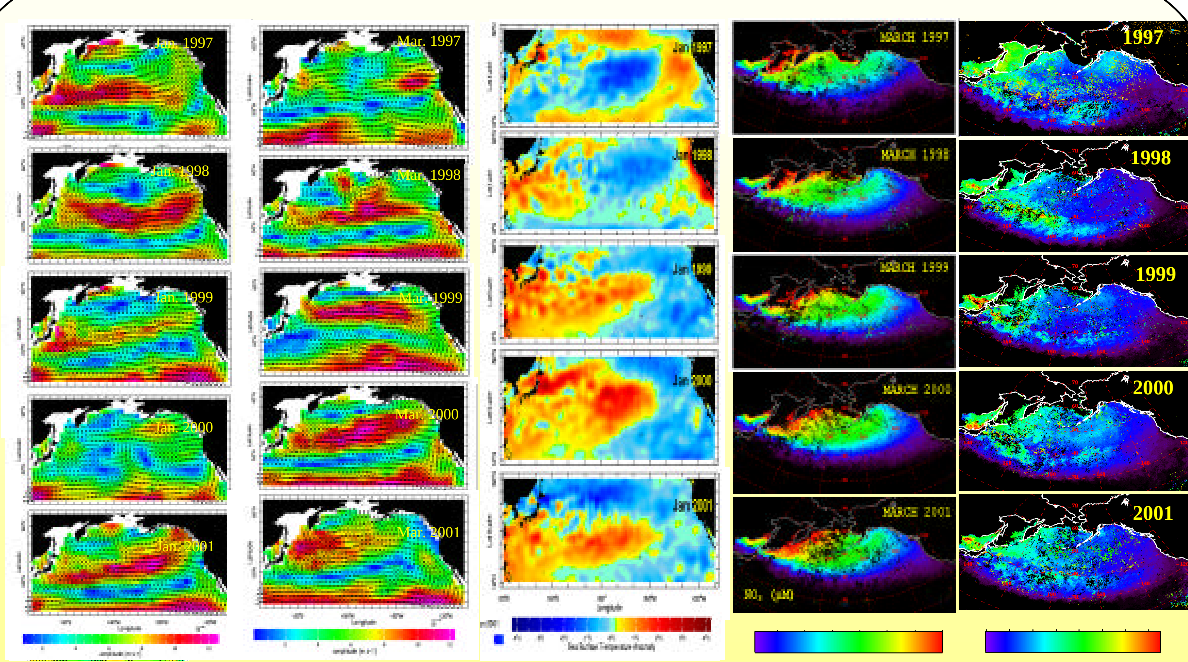
METHODS AND DATA SOURCES

Annual rates of carbon export were estimated using the satellite based approach described in Goes *et al*., 1999, 2000. In brief, the method utilizes satellite derived SST and chl *a* to obtain estimates of sea surface nitrate (SSN). In this study, satellite derived chl *a* (GAC Level 3, monthly binned OCTS and SeaWiFS data from DAAC) and SST (Pathfinder global gridded, 9 km, monthly average, daytime data from PODAAC) from 1997-2002 were utilized to obtain estimates of SSN. Using a C:N ratio of 106:16, and a satellite based estimate of the depth of the nitracline above which nitrate is consumed, nitrate based new production was calculated as described in Goes et al. (2000, 2001). Interannual variations in new production for the five year period were then analyzed in the context of prevailing oceanographic and meteorological conditions. Monthly composites of meridional sea surface winds and SST anomalies were obtained from the Integrated Global Ocean Services System (IGOSS) Products Database at Lamont-Doherty, USA. Shipboard sea water temperature, Mixed Layer Depths (MLD), nitrate and chl *a* were obtained from 1) the Japan Oceanographic Data Center (1972-2000) and 2) Hokkaido National Fisheries Institute A-line transect data (1990-2000). The 2° latitude-longitude monthly summaries of marine meteorological variables obtainable from COADS were used to calculate wind stress according to Iwasaka and Hanawa (1990). The latitudinal-longitudinal boundaries of the Oyashio front denoted as the Southern Limit of the First Oyashio Intrusion (SLFOI) are based on the temperature at 100 m and described in (Limsakul *et al.* 2002).



Interannual variations in meteorological indices and in wind stress, mixed layer depths, mixed layer nitrate, southern limit of the Oyashio current and column integrated annual chl *a* from 1997-2001

Averages of the Southern Oscillation Index (SOI) for November to March, reveal that they were 5 El-Niño events from 1976 to 2001. Of these, the events of 1982/83, 1986/87, 1992/93, 1997/98 were very strong. Following the onset of each El-Niño event, the area-weighted sea level pressure over the region 30°N-65°N, 160°E-140°W (the NPI) decreased. These changes in atmospheric conditions were clearly responsible for the anomalous southward penetration of the Oyashio current (NPI vs SLOFI) and the increase in the atmospheric pressure gradient between the Eurasian landmass and the subarctic gyre (NPI vs MOI). The monsoonal index (MOI), an index of the steepness of this gradient, showed a strong positive correlation with wintertime wind stress (MOI vs wind stress), suggesting that interannual variations in the pressure gradient between the Eurasian landmass and the subarctic gyre have a profound impact on westerly winds over the subarctic Pacific. As is clear from the strong correlation between winter wind stress and SST, and winter wind stress and wintertime mixed layer depths (MLDs), wintertime winds exert a strong influence on convective mixing in the subarctic gyre. The spatial extent of the region that came under nutrient rich waters (measured by the Southern Limit of the First Oyashio Intrusion (SLFOI)) was also far greater following an El-Niño event as compared to a normal year. The cumulative effect of these changes is that, they led to a marked increase in biological productivity in the western North Pacific Ocean. The positive impact of the changes on the regions biology is clearly visible in the prominent peaks of shipboard annual water column integrated chl *a* that are coincident with El-Niño events. These findings from the shipboard archived data, help corroborate our results from the satellite data which suggested that the primary driver for the observed interannual variations in biological production in the western subarctic Pacific is the strength of the wintertime monsoonal winds, which is influenced by changes in the strength and the position of the Aleutian Low.



Wind stress in winter (m s^{-1}) **Wind stress in spring (m s^{-1})** **Sea Surface Temperature Anomaly (°C)** **Sea Surface Nitrate (mM)** **New Production (gC m^{-2} yr^{-1})**

Interannual variations in mean surface wind stress vectors (m sec-^{1}) for January and March 1997-2001 and monthly composites of SST (°C) anomalies for January 1997-2001

Interannual variations are seen in both the strength of the westerly winds and the position of its axis across the subarctic basin. January 1997 which coincided with the El-Niño event was the windiest, and the region from the coast of Japan to approx. 170°W showed maximum wind stress. In January 1998, the belt of strong westerly winds moved northwards over the western subarctic gyre and the area of maximum wind stress was displaced to the east at around 180°E extending close to the west coast of North America. Wind stress vectors for the winters of 1999 and 2000 were the weakest. Wind stress vectors for March and the beginning of spring indicated a northward migration of the belt of westerlies and a general weakening of the winds. The spring of 1997 was the calmest although this year had the windiest winter of all five years. In contrast, year 2000 which had the calmest winter had the windiest spring.

SST anomalies for January 1997-2001 showed that the winter of 1997 was the coolest. The region of negative SST anomalies extended beyond the central subarctic Pacific to about 150°W. In contrast, except for the cold water mass close to the coast of North America, the region offshore, to the west of 120°W was characterized by SST positive anomalies. By 1998, SST anomalies in the west subarctic gyre, changed signs to represent warmer waters. The region of negative anomalies was displaced in the central subarctic Pacific centered at about 150°W and 40°N. The entire coast of North America was clearly warmer during this winter. In the following years the western and central subarctic regions were warmer than their climatological counterparts, but the entire region close to the coast of North America and the eastern subarctic gyre became cooler.

Spatial distribution of SSN in March and annual rates of New Production from 1997-2001

Interannual variations in sea surface nitrate (SSN) concentrations for March - the start of the growth season of phytoplankton provide clear evidence of temporal and spatial variations in the distribution of SSN. Nitrate inputs were clearly higher north of 25°N as compared to the region south of this latitude, and, greater in the western subarctic Pacific, west of 160°W than in the eastern subarctic gyre. The differences were particularly conspicuous along the eastern and western boundaries of the subarctic Pacific Ocean, where the effects of winter time winds and the depth of winter-time convective mixing are clearly visible. By the end of the winter that followed the El-Niño event of 1997 nitrate concentrations were lower along the entire west coast of North America. In contrast, the western North Pacific showed a contrasting picture with far greater nitrate inputs during the same period.

Annual rates of new production ranged between 1 to 70 g C m^{-2} yr^{-1} and for the 5-year period showed greater interannual variability than that observed in the SSN maps. In the eastern subarctic, new production from 1997 to 2001 was much lower than in the western subarctic and a clear interannual pattern was not discernable. In the western subarctic in 1997 and 1998, a vast expanse of elevated new production was observed that tracked the southern edge of the subarctic gyre and traveled beyond 160°W. By 1999, this swath of high new production diminished both in length and breadth and was seen as a minor extension of the region of elevated new production located in the western subarctic gyre. In 2000, new production values were clearly the lowest of all five years. In 2001, the area of annual new production in the western half and west of 170°E showed high new production values but the swath of elevated new production values did not extend beyond 170°E.

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