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Maslowski, Wieslaw; Cassano, John J.; Walsh, John J.

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**2008 Report for the project entitled:
A Comprehensive Modeling Approach Towards Understanding and Prediction of
the Alaskan Coastal System Response to Changes in an Ice-diminished Arctic**

Wieslaw Maslowski
Department of Oceanography
Graduate School of Engineering and Applied Sciences
Naval Postgraduate School
833 Dyer Road, Monterey, CA 93943
Phone: (831) 656-3162 FAX: (831) 656-2712 E-mail: maslowsk@nps.edu

John J. Cassano
Cooperative Institute for Research in Environmental Sciences
University of Colorado at Boulder
Boulder, CA 80309-0216
Phone: (303) 492-2221 FAX: (303) 492-1149 E-mail: cassano@cires.colorado.edu

John J. Walsh
College of Marine Science
University of South Florida
140 Seventh Avenue, South
Saint Petersburg, FL 33701-5016
Phone: (727) 553-1164 FAX: (727) 553-1189 E-mail: jwalsh@seas.marine.usf.edu

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LONG-TERM GOALS

Our research combines state-of-the-art regional modeling of sea ice, ocean, atmosphere and ecosystem to provide a system approach to advance the knowledge and predictive capability of the diverse impacts of changing sea ice cover on the bio-physical marine environment of coastal Alaska and over the larger region of the western Arctic Ocean. The focus of this project on seasonally ice-free Alaskan coasts and shelves is in direct support of the 'Coastal Effects of a Diminished-ice Arctic Ocean' and littoral studies of interest to the U.S. Navy.

Given the continued warming and summer sea ice cover decrease in the Arctic during the past decades, this research will have broader and long-term impacts by facilitating studies of the potential increased exploration of natural resources along the seasonally ice-free northern Alaskan coasts and shelves and of the use of northern sea routes from the Pacific Ocean to Europe. Such activities will change the strategic importance of the entire pan-Arctic region. The research will allow a better understanding and planning of current and future operational needs in support of the continued US commercial and tactical interests in the region.

OBJECTIVES

The main science hypothesis to be addressed in this project can be formulated as follows. The recently observed dramatic decrease of summer sea ice cover in the western Arctic Ocean is driven by two main, primarily local factors: (i) the oceanic heat advection of summer Pacific Water via the Alaska Coastal Current and (ii) the positive ice-albedo feedback. To understand physical processes and air-sea-ice interactions involved in these two driving factors, detailed studies, including historical and new observations and very high-resolution modeling, of the Alaska coastal environment are required. The following five specific science goals are proposed to address those requirements in support of the main hypothesis of this project:

1. Explore feedback processes among sea ice, ocean and atmosphere leading to recent and possible future summer decreases of sea ice cover in the Western Arctic Ocean;
2. Quantify impacts of oceanic and atmospheric forcing on regional sea ice cover and its variability;
3. Determine effects of changing sea ice, ocean dynamics and atmospheric circulation on the Alaskan coastal ecosystem (due to temporal and spatial variability);
4. Establish numerical requirements for an optimal hindcast and prediction of environmental conditions in the Alaskan coastal system;
5. Provide guidance for optimal design of an integrated observing system of the Alaskan coastal environment.

APPROACH AND WORK PLAN

This work builds on a wealth of Arctic modeling expertise and progress at the Naval Postgraduate School, University of Colorado, and University of South Florida to develop state-of-the-art, regional ocean, sea ice, atmosphere and ecosystem models satisfying requirements for studying this coastal system (Maslowski et al., 2007a, 2007b; Maslowski et al., 2004; Maslowski and Lipscomb 2003; Maslowski and Walczowski, 2002; Maslowski et al., 2001; Maslowski et al., 2000; Clement et al., 2005; Clement et al., 2007; Cassano et al., 2001; Cassano et al., 2006a, 2006b, Cassano et al., 2007; Walsh et al., 2004; Walsh et al., 2005). This effort will use available historical and new data for validation or initialization.

Atmospheric Modeling: The group at CU plans to complete a suite of varied horizontal resolution atmospheric model simulations over a model domain centered on the Alaskan north slope using ERA40 initial and lateral boundary conditions and sea ice extent from satellite observations. All simulations are to be nested within coarser resolution regional atmospheric model domains that cover a larger portion of the Arctic, such that the change in resolution between any domain forcing data (either from global reanalyses or coarser resolution atmospheric model domains) and that domain's horizontal resolution is no greater than a factor of 5. In addition to this basic suite of atmospheric model simulations we will perform an ensemble of simulations at 50 km horizontal grid spacing to assess the model sensitivity to the source of lateral forcing data, by using global NCEP/NCAR reanalysis data, and to the choice of atmospheric model by using Polar MM5 and Polar WRF. All model output will be freely shared with our project collaborators at the Naval Postgraduate School.

Ice-Ocean Modeling: The NPS personnel led by Dr. W. Maslowski have developed bathymetry, initial and forcing fields for an eddy resolving configuration. The model at 1/48-degree has started the spinup integration, which will continue for through 2009 and beyond, subject to the availability of large amount of computer resources and model performance on new computer systems becoming available this year (ARSC/XT5 and NPS/Sun Cluster).

Ecosystem Modeling: research is led by Dr. John J. Walsh at the University of South Florida. The milestones of this project involve completion of the following four tasks:

1. Modify the existing 9-km bio-model of Walsh et al. (2004, 2005) to allow decadal integrations
2. Develop a biological (N-P-Z) model at eddy-resolving resolution and over the same domain as the ocean-ice model
3. Complete two decadal simulations (configured at increasing spatial resolution) of the biological model forced with high-resolution ice-ocean and atmospheric model output
4. Analyses (inter-comparison of various model runs and validation with historical and new data) of results to address the main science goals

WORK COMPLETED / RESULTS

University of Colorado

The researchers at the University of Colorado in Boulder have completed two 20 year 100 km horizontal resolution pan-Arctic simulations using the Polar MM5 atmospheric model for the period 1980 to 1999. One simulation used ERA40 data for the model initial and lateral boundary conditions. The second simulation also used ERA40 data as the initial and lateral boundary conditions but also used four dimensional data assimilation to nudge the upper atmospheric portion of the model domain towards the ERA40 atmospheric state. Analysis of these simulations indicated significant problems with the Polar MM5 simulations on this large pan-Arctic domain. Since MM5 is no longer being actively developed by the atmospheric science community and is being replaced as the primary US mesoscale atmospheric model by the Weather Research and Forecasting (WRF) model, it was decided that no additional simulations would be performed for this project using the Polar MM5. We are currently working towards the development of a polar optimized version of WRF, which will be suitable for the atmospheric modeling portion of this project. We expect to have a final Polar WRF configuration established by late fall 2008. Once this model configuration is finalized we will begin running a suite of pan-Arctic simulations at varied horizontal resolution.

Naval Postgraduate School

Research contributions at NPS have focused during 2008 on three main efforts. First, we have performed analyses toward understanding of oceanic circulation and mechanisms contributing to the recent warming in the western Arctic Ocean (Maslowski and Clement Kinney, 2009). We have analyzed numerical model output validated with available observations to determine the relative importance of the internal oceanic forcing of sea ice melt. In particular, the thermodynamic coupling at the ice-ocean interface in the western Arctic Ocean has been investigated. Under-ice ablation by anomalously warm water advected from the Chukchi shelves and distributed at the subsurface layer in the western Arctic Ocean by mesoscale eddies has been found to explain at least 60% of the total variance of sea ice thickness. We have demonstrated that the excess oceanic heat that in recent years has been accumulating below the surface during summer and it might be a critical initial factor in reducing ice concentration and thickness in the western Arctic Ocean at the early melting season and onwards the following year.

Second, we have investigated the 9-km model skill in representing eddies in the Chukchi/Beaufort sea (Maslowski et al., 2008). Spectral analysis of model and altimeter-measured sea surface topography over the Gulf of Alaska and in the Bering Sea suggest that the 9-km grid is not sufficient to fully resolve eddy features with wavelengths shorter than 100-150 km. Our regional analyses imply that spatial resolution of order few kilometers is needed to fully represent eddy energetics in the Arctic Ocean. In order to improve understanding of the role of mesoscale eddies on the regional ocean dynamics progress has been made toward the development of the fully eddy-resolving model of the Arctic Ocean. The initial and forcing fields have been prepared and integrations started of the eddy-resolving model configured at 1/48-degree and 48 vertical levels. Our early results

(Figure 1) imply that eddies with radius of order 15 km commonly exist along the northern Alaskan shelf and slope in the Chukchi and Beaufort seas. In addition, the significantly narrower and stronger boundary current along the continental slope is simulated with the width between 60 km and 80 km, which is less than the size of one grid-cell in many global ocean models.

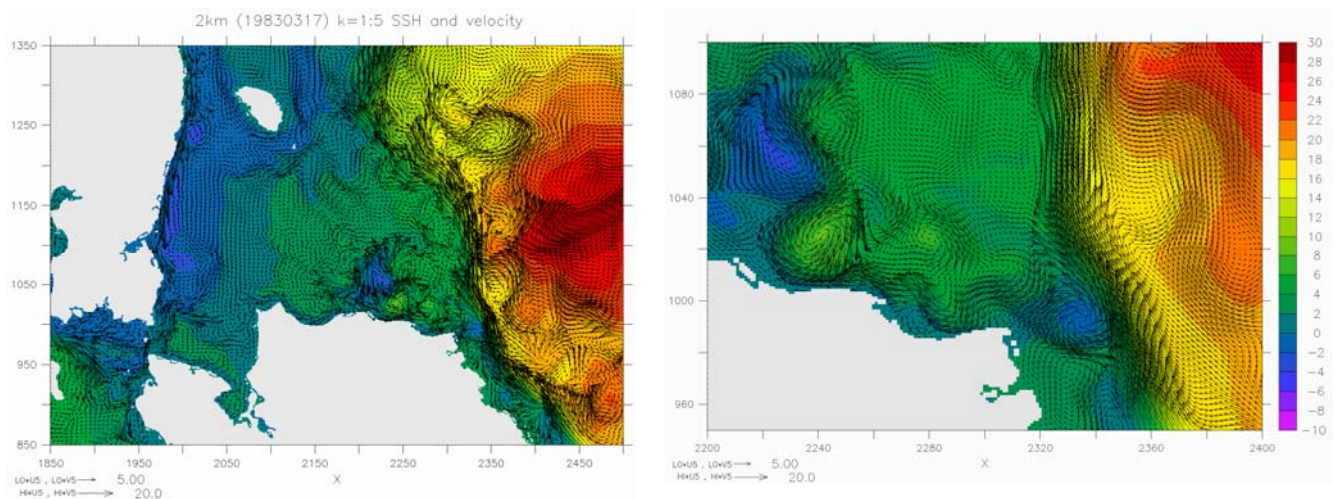


Figure 1. Sea surface height (color shading; cm) and depth-averaged velocity (cm/s) in the upper 25 m over the Chukchi and Beaufort seas from the NPS eddy-resolving model on March 17, 1983. The right panel shows enlarged subset of the left panel with mesoscale eddies along the North Slope Alaska and in the Barrow Canyon.

Third, we have made progress in understanding the past and present states of the environmental change in the Arctic and attempted projections of future scenarios. In particular we have analyzed results on melting sea-ice from our regional ice-ocean model and demonstrated their robustness independent of timescales for surface temperature and salinity relaxation (Maslowski et al., 2007). Our results show that observed sea-ice cover variability is realistically represented in the model. In addition, we find that the ice thickness and similarly volume have been decreasing even faster than the ice area or extent, which implies that the rate of melt might be under-estimated if only the aerial changes in the Arctic sea ice are considered. Limited ice thickness observations appear to confirm such a conclusion, which implies that near ice-free summer conditions could occur in the Arctic much earlier than previously expected.

University of South Florida

As part of the USF contribution to this joint NOPP project, a nitrogen isotope budget for contiguous Arctic marine ecosystems of the Gulf of Alaska, the northwestern Bering Sea, the Chukchi Sea, and East Siberian Sea, as well as the western (Mackenzie River plume) and eastern (Lancaster Sound) sectors of the Beaufort Sea was recently completed (Walsh et al., 2008). This analysis both identified the common threads of regional food webs, supporting threatened mammals (polar bears, bowhead whales, gray whales, and humans) of the western Arctic, and which of their state variables must be included in realistic coupled UC atmospheric, NPS sea ice and circulation, and USF ecological models to address the future consequences of lost ice cover.

Global warming has led to reduced ice cover in the Arctic, increased water temperatures, and perhaps increased desertification of adjacent lands, i.e. the Gobi desert. Loss of ice habitat has direct consequences, of course, for food resources of the polar bear predator, *Ursus maritimus*, at the top of the marine food web. These bears eat seals, feeding on fish, which in turn harvest other fish,

consuming the zooplankton herbivores of the sea. But, over the last 50 years other cetacean mammals, which instead feed at intermediate levels of the food web, reflect past and possible future changes of the phytoplankton at the bottom of the polar food web. During the last half century, the isotopic signature of $\delta^{15}\text{N}$ from nitrogen-fixation, left behind in baleen plates of bowhead whales, *Balaena mysticetus*, has increased.

Over a shorter decadal time scale, from 1988 to 1998, the same isotopic $\delta^{15}\text{N}$ signature of an apparent increased contribution of diazotrophs to Arctic primary production was also recorded in muscle tissue of bowheads, harvested from the Beaufort Sea. However, adult and juvenile *B. mysticetus* derive only ~10% of their diet from the eastern Beaufort Sea, feeding instead on copepods and euphausiids within the Chukchi Sea, while migrating to their wintering grounds in the western Bering Sea. Thus, local nitrogen-fixation at low Arctic temperatures of the Beaufort Sea need not be invoked.

Instead, the diazotrophic marker of particulate nitrogen within bowhead whale baleen and muscle may result from advective imports of downstream zooplankton prey, labeled indirectly by growth of *Trichodesmium* farther south in the North Pacific Ocean, after deposition episodes of iron-rich dust from the Gobi Desert. During NASA satellite imagery of an eastward propagation of Gobi dust during 2001, Asian aerosols were also observed at ground stations on both Adak Island and at Fairbanks in March-April 2001. But, smaller amounts of Asian dust were then found at Fairbanks, suggesting significant deposition of crustal elements over the intervening Bering Sea. Among such crustal components is iron, of course, which is required for synthesis of the nitrogenase enzyme, used by marine phytoplankton, e.g. *Trichodesmium*, during nitrogen-fixation in the North Pacific Ocean,

These baleen whales eat plankton herbivores, copepods and euphausiids, which also have the isotope signal of consumption of nitrogen-fixers within warmer waters of the deep basin of the Bering Sea. Here, nitrogen-fixers grow well in warm waters, underneath aerosol plumes of iron-rich dust from the Gobi Desert. During this same time period, the areal extent of summer Arctic sea ice cover had been reduced by 30%, between 1950 and 2000, which should have favored phytoplankton adapted to both high light conditions and low nutrient stocks. Such a species transition of the phytoplankton community was observed as imports, north of Bering Strait by 2003, of coccolithophores, toxic dinoflagellates, microflagellates, and diazotrophs from downstream boreal and subtropical ecosystems. Furthermore, at lower latitudes, Saharan dust plumes in the Gulf of Mexico also favor not only nitrogen-fixers, but a species succession of phytoplankton to a fish-killing dinoflagellate *Karenia brevis*, which leads to annual economic losses of 25 million dollars during some years along the US seaboard, from Texas to North Carolina.

Moreover, of the many species of abundant dinoflagellates found by us in the Chukchi Sea during 2003, *Alexandrium tamarense* is of particular interest. Previously known as *Gonyaulax* spp., related species of *Alexandrium* now cause toxic red tides of paralytic shellfish poisoning (PSP) in other cold water environments of both the North Sea and the Gulf of Maine. Early saxitoxin symptoms of nausea, dryness of the throat, numbness of the lips, and disorientation, after consumption of blue mussels, *Mytilus edulis*, resulted in the deaths of ~100 Aleut hunters near Sitka Island in July 1799, first recorded as an unknown PSP event by Aleksandr Baranov. A few years earlier in 1793, one crew member of a British survey of southwestern Canadian waters had also died, with similar PSP symptoms, about 5 hours after a toxic breakfast of mussels. About 200 years later, other toxic PSP events were recorded along this same coastal region of southeastern Alaska, where the Koniag Indians and Chugach Eskimos were instead familiar with seasonal toxicity of shellfish, before the 18th century.

More recent outbreaks of known PSP events, reported to the Alaska Division of Public Health, were found mainly south of the Aleutian Island chain, within the Gulf of Alaska, between 1954 and 1994 and then attributed to *A. catanella* and *A. tamarense*. However, other populations of *A. excavata* were also noted in relation to deaths of marine mammals, fish, and sea birds within the Bering Sea to

the northeast of Kamchatka by 1986. Thus far, local Arctic populations of *A. tamarensis* amounted to only 10-50% of the total carbon biomass of all dinoflagellates in the Chukchi/Beaufort Seas during July-August 2003. Yet, just a year before, they contributed only ~5% of the carbon biomass of all these dinoflagellates within a few samples from the same regions in July-August 2002. We thus included this functional group of phytoplankton in our model.

Other members of the macrobenthos, in addition to the co-dominant bivalve mollusks, which are now harvested by both humans and walrus, *Odobenus rosmarus*, are the large amphipod herbivores *Ampelisca macrocephala*. They are eaten mainly in the northern Bering Sea by California gray whales, *Eschrichtius robustus*, just now recovering from past human exploitation and harvesting these benthic herbivores, like the baleen whales eat the pelagic ones. Future warmer temperatures would favor faster growing, smaller competitors of *A. macrocephala*, while their response to increased PSP events is unknown.

Will present toxic phytoplankton blooms of the North Sea, the Gulf of Maine, the Gulf of Mexico, and the downstream South Atlantic Bight also follow reduced ice cover and warmer temperatures in future Arctic seas? Accordingly, to deal with these potential future Arctic food chain oscillations, we then asked (Walsh et al., 2008) what were the biotic consequences of interannual physical perturbations of ice cover, vertical mixing, and water transport for transfer of light energy and elements of N, P, Si, C, and O₂ through a model food web of six functional groups of phytoplankton [diatoms, dinoflagellates, coccolithophores, colonial prymnesiophytes, microflagellates, and diazotrophs], constrained by grazing losses to three groups of herbivores [protozoans, copepods, and benthic macrobenthos] during 2002-2004, when extensive validation data were obtained from the East Siberian, Chukchi, and Beaufort Seas.

Thus, the dissolved nutrients and gasses (NO₃, NH₄, N₂, PO₄, DOP, SiO₄, O₂, CO₂) were also impacted by two groups of bacterioplankton (ammonifiers and nitrifiers), summing to 28 explicit state variables of the combined models [wind; temperature; salinity; ice cover; spectral light; **u**, **v**, **w** vectors of flow; vertical mixing coefficient, K_z; UV-sensitive colored dissolved organic matter (CDOM); equivalent labile DOC, DON, and DOP; the other five forms of inorganic nitrogen (NO₃, NH₄), phosphorus (PO₄), silicon (SiO₄), and carbon (DIC) nutrients; dissolved oxygen as an index of net photosynthesis; ammonifying and nitrifying bacteria; the six groups of phytoplankton, for which cell counts were made at the species level during 2002 and 2003 cruises, with additional use here of satellite algorithms to distinguish among the two groups of backscattering coccolithophores and diazotrophs and the other phytoplankton groups; fecal pellets of protozoan and copepod herbivores; and interactions of the amphipod herbivores with sediment detritus]. The time domain was from 15 July 2002 to 15 October 2004, at daily intervals.

The vertical extent of the coupled models at 9-km horizontal resolution consisted of 45 layers of varying thickness over the water column, covered in some regions by ice, and underlain at the sea bottom by a 1-cm thick layer within surficial sediments. At each hourly time step of the model at each spatial grid point, the computed temperatures from the circulation model, as well as the computed light and unutilized nutrient fields from the last time step, were compared to the optimal growth parameters for maximal growth of each functional group of phytoplankton, based upon: Q₁₀ thermal impacts; saturation light intensities and ambient light; as well as the required Redfield ratios of C/N/P for balanced growth, as well as Si for diatoms, and the model's dissolved nutrient pools. Among these thermal, light, and nutrient constraints, the minimal net particulate growth of each phytoplankton group was next implemented, after subtraction of respiration and excretion losses. Thence, appropriate grazing and settling losses were also imposed, with transfer of these hourly phytoplankton element fluxes to the model's pools of bacterioplankton, zooplankton, macrobenthos, detritus, dissolved organic matter, maintaining mass balances of the marine, sediment, and atmospheric reservoirs of each element.

Our strategy for simulation analyses involved numerous data sets from: eight cruises over the model's spatial domain; other moorings and helicopter surveys at the south and north boundaries of the coupled model for assimilation data; and satellite overflights during 2002-2004. The *Polar Star*, *Healy*, *Mirai*, and *Louis St. Laurent* cruises during July-October 2002 provided initial conditions. The helicopter surveys and Bering Strait moorings during April 2003 represented data for two contrasting cases of assimilation and ignorance of winter information. The extensive *Alpha Helix* and *Nathaniel Palmer* observations in July-August 2003 were validation data, with least square fits to the two model cases for assessment of the coupled model's fidelity. Finally, the *Khromov* and *Healy* data during June-October 2004 represented a second case of validation information, albeit of less spatial richness than the 2003 studies.

IMPACT AND APPLICATIONS

National Security

The focus of this project on seasonally ice-free Alaskan coasts and shelves is in direct support of the ONR focus on 'Coastal Effects of a Diminished-ice Arctic Ocean' and littoral studies of interest to the U.S. Navy. Given the continued warming and summer sea ice cover decrease in the Arctic during the past decades, this research will have broader and long-term impacts by facilitating studies of the potential increased activities along the seasonally ice-free northern Alaskan coasts and shelves. Such activities will change the strategic importance of the entire pan-Arctic region. The research will allow a better understanding and planning of current and future operational needs in support of the continued US tactical interests in the region.

Economic Development

Understanding and prediction of environmental conditions under a diminished-ice Arctic Ocean will have broader and long-term impacts by facilitating studies of the potential increased exploration of natural resources along the seasonally ice-free northern Alaskan coasts and shelves and of the use of northern sea routes from the Pacific Ocean to Europe. The research will allow a better understanding and planning of current and future operational needs in support of the expanding US commercial interests in the region.

Science Education and Communication

The project involves undergraduate, graduate, and postdoctoral education in research. The postdoctoral and graduate students will receive practical training in environmental modeling and/or analysis of model output and observational data. All PIs will present results of this research in undergraduate and graduate classes, at scientific meetings and in peer-reviewed literature.

RELATED PROJECTS

This grant is funded by the Office of Naval Research's National Oceanographic Partnership Program (NOPP), and builds on work done under the two following programs funded by NSF:

1. Study of Northern Alaska Coastal System (SNACS): Maslowski and Cassano (co-PIs)
2. Western Arctic Shelf Basin Interaction (SBI): Maslowski and Walsh (co-PIs)

More information about the two projects is available at www.oc.nps.navy.mil/NAME/name.html

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- Cassano, J.J and M.W. Seefeldt, Development and evaluation of Polar WRF. Little Alaska Weather Symposium, Fairbanks, AK, May 2008.
- Cassano, J.J and M.W. Seefeldt, Development and evaluation of Polar WRF. Antarctic Meteorological Observation, Modeling, and Forecasting workshop, Madison, WI, June 2008.
- Maslowski, W., On Rates of Arctic Sea Ice Decline, NSIDC Seminar, Boulder, CO, 18 January, 2008.
- Maslowski, W., On Projections of ice-free Summers in the Arctic Ocean, Tokyo University of Marine Science and Technology, Tokyo, Japan, 20 June, 2008.
- Maslowski, W., When will Summer Arctic Sea Ice Disappear? Sustainability Weeks 2008 - Symposium on Drastic Change in the Earth System during Global Warming, Sapporo, Japan, 24 June, 2008.
- Maslowski, W., Warming Arctic Climate – Causes, Changes, and Impacts, invited seminar at the Center for Computational Sciences, Tsukuba University, 28 October, 2008.
- Maslowski, W., Rate and Future Projection of Arctic Climate Change – An Update, First International Symposium on the Arctic Research, November 4-6, 2008
- Maslowski, W., Causes, Rates and Consequences of Warming Arctic Climate, invited seminar during the United Nations Framework for Climate Change Conference 14, Polish Academy of Sciences, Poznan, Poland, 11 December, 2008.
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