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全球表面增暖减缓期间渤海海冰分布范围遥感探测及海洋内部温度异常遥感感知

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Remote sensing of the extent of the Bohai sea ice and temperature anomaly of ocean interior during recent global surface warming hiatus

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内 容 摘 要

自 1998 年起，全球表面出现增暖减缓，全球气候处在深度调整中。我国近岸对此出现不同程度的响应，极端海洋灾害事件频发。2009-2010 年冬季，受北方持续寒潮的影响，渤海出现了历史罕见的严重海冰冰情，海冰成为 2010 年中国海洋主要灾害之一。通过冰冻区遥感影像分类准确有效地提取海冰分布信息对于检测和评估海冰演化过程是至关重要的。我们提出一种新的基于融合多特征的机器学习影像分类技术，有效地用于 MODIS 冰冻区影像分类及海冰分布范围估算。通过灰度共生矩阵（GLCM）纹理特征分析提取 MODIS 影像纹理特征，通过劈窗算法反演 MODIS 海表温度信息，最后利用融合多特征信息（光谱特征、纹理特征及海表温度特征）的支持向量机（SVM）分类方法进行 MODIS 冰冻区影像分类及海冰信息提取，与传统的基于单一光谱特征的图像分类技术相比，通过同时相较高空间分辨率的 H1B-CCD 影像验证及精度评价，该方法提高了海冰可探测性与识别精度，说明融合纹理特征与海表温度特征有助于机器学习法的 MODIS 海冰信息提取，可为冰情实时有效监测提供技术支持。

全球增暖减缓期间中深层海洋（300-2000 m）变暖趋势明显，中深层海洋在全球增暖减缓过程中扮演着“储热器”的重要角色。全球增暖减缓的研究需要全球尺度的长时间序列的观测数据作为支撑，对海洋数据在时空连续性方面（特别是次表层到中深层的数据）提出了新的需求，急需发展深海遥感观测技术。在全球增暖减缓期间，我们突破性地采用支持向量机（Support Vector Machine，SVM）高级机器学习的方法，从表层多源卫星遥感观测（SST、SSH 与 SSS）估算次表层温度异常（STA），利用 Argo 现场观测数据做验证，与传统的统计回归方法对比，新方法提高了海洋内部温度结构的反演精度，为中深海热力参量遥感研究提供有力的技术手段，可用于构建可靠的中深海热力结构数据集，从而优化中深层海洋增暖分析。

全球增暖减缓期间，我们利用多套资料（WOD，MyOcean，ECMWF-ORAS4）研究发现当前全球中深层海洋（300-2000 m）增暖显著（10^{22} 焦耳数量级），并且世界各个大洋（包括大西洋、太平洋、印度洋及南大洋）都有不同程度的贡献，

印度洋的作用较为显著不可忽视。但是，不同资料所反映的增暖幅度与趋势存在差异，揭示了当前中深层海洋暖化对全球增暖减缓的贡献存在较大不确定性，这主要是中深海观测数据有限所致。没有充足完整可靠的数据集，没有气候研究群体的良好协调，我们很难完全认识全球增暖减缓的机理，并在寻找地球表面“失踪热量”这一问题上达成共识，更不可能对增暖减缓期的持续时间做出预测。在研究全球增暖减缓这样的问题时，对全球海洋进行地理上的硬性分割，或是只专注于某个区域对全球气候的影响，都无异于盲人摸象。

关键词：全球表面增暖减缓；中深层海洋暖化；中深层海洋遥感；海冰分布范围估算；支持向量机

Abstract

Since 1998, the global warming trend enters hiatus, meanwhile the global climate is under in-depth adjustment. The coast of China intensively responds to recent hiatus with frequent extreme marine disasters. A continuous cold snap in the 2009-2010 winter caused a rare and severe sea ice accumulation in the Bohai Sea. Sea ice has become one of the major marine disasters of China in 2010. The image classification of frozen areas and adjacent sea ice is important for monitoring the evolution of ocean freezing. This study proposes a novel approach based on machine learning to the MODIS image classification and sea ice extent estimation in frozen areas. We extracted MODIS texture feature (TF) by a Gray Level Co-occurrence Matrix (GLCM), and retrieved the MODIS surface temperature (ST) using a split-window method, finally classified the image for sea ice extent estimation using a Support Vector Machine (SVM) convoluting the ST and TF method. Results were compared and validated with those of conventional spectral-based supervised classification approaches. Results show that the overall accuracy and Kappa coefficient using the proposed method much higher in comparison with those of the spectral-based Maximum Likelihood and SVM methods. The SVM fusion ST and TF method was effective and useful for MODIS 500m image classification and sea ice mapping in frozen area. Combining ST and TF can improve MODIS sea ice detectability and recognition accuracy in the frozen Bohai Bay.

Accurately detecting and describing the subsurface thermal structure of the global oceans is an important aspect of ocean dynamics. Subsurface and deeper ocean thermal remote sensing is becoming even more important since new evidence suggests widespread warming in the global subsurface and deeper ocean (300-2000 m) as a response to the global climate variability and change. We propose a support vector machine (SVM) method to estimate subsurface temperature anomaly (STA) over large basin-wide scale from a suite of satellite remote sensing measurements (SSTA, SSHA, SSSA). SVM can well estimate the STA in the upper 1000 m of the Indian Ocean from satellite measurements of sea surface parameters. Moreover, our method can improve the analysis of deeper ocean warming, and provide a useful technique for studying subsurface and deeper ocean thermal variability which has played an important role in recent global surface warming hiatus from satellite measurements in large basin-wide scale.

According to the multisource datasets (WOD, MyOcean and ORAS4), the rapid increase of subsurface and deeper ocean (SDO, 300-2000 m) heat content with order of magnitude of 10^{22} joules over the world ocean basins plays an important role in the recent global surface warming hiatus, and almost all ocean basins (including the Atlantic Ocean, Indian Ocean, Pacific Ocean and Southern Ocean) are jointly contributing to the current hiatus. The heat uptake from the subsurface and deeper layers of the Indian Ocean is about $0.87*10^{22}$ joules on average, accounting for about 21% of global SDO heat increasing during recent hiatus, suggesting the role of the Indian Ocean is significant. The combined use of the different datasets may help identify the uncertainties in the deeper ocean warming analysis, and improve the understanding of the role of the deeper ocean in the recent global surface warming hiatus. The widespread warming of the global SDO has sequestered a significant amount of heat about $4.07*10^{22}$ joules on average, and makes great contributions in maintaining the current hiatus, but there is still large uncertainty in current deeper ocean warming and surface warming hiatus study due to the data limitation. Without more datasets that make sense holistically, and without a well-coordinated climate science community effort, it is not possible to fully understand the mechanisms, reach a consensus on finding the Earth's missing heat, and predict the current global warming hiatus. The parable of blind men and the elephant shall remind us that when dealing with a phenomenon of global scale, demarcating the global ocean or focusing on certain regional variability will render merely a partial understanding of the subject.

Keywords: global surface warming hiatus; subsurface and deeper ocean warming; deeper ocean remote sensing; sea ice extent estimation; support vector machine

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Chapter 1. Introduction

1.1 Background

The observed global mean surface temperature (GMST) has shown a much smaller increasing linear trend over the past 15 years than over the past 30 to 60 years (Flato et al., IPCC AR5, 2013). The 15 year period referred to in the IPCC report is 1998-2012 and this continuing phenomenon is known as the global warming hiatus. The global warming hiatus is occurring despite the continued increase in atmospheric CO_2 concentrations (Easterling & Wehner, 2009; Foster & Rahmstorf, 2011; Kosaka & Xie, 2013). There is, as of yet, no consensus on the mechanisms behind the global warming hiatus. As a global climate issue, studying the recent hiatus is quite important, but a real multidisciplinary challenge.

The global warming trend enters hiatus since 1998, meanwhile the global climate is under in-depth adjustment. The coast of China intensively responds to recent hiatus with frequent extreme marine disasters. A continuous cold snap in the 2009-2010 winter caused a rare and severe sea ice accumulation in the Bohai Sea. Sea ice has become one of the major marine disasters of China in 2010. During recent hiatus, the severe sea ice disaster occurs frequently in the Bohai Sea in winter.

Subsurface and deeper ocean thermal remote sensing is becoming even more important since new evidence suggests widespread warming in the world's deeper ocean as a response to the global climate variability and change (Song & Colberg, 2011; Balmaseda et al., 2013). Deeper ocean remote sensing is becoming even more significant than ever since there are indications that the deeper ocean is warming up and has played an important role in recent global surface warming hiatus since 1998 (Chen & Tung, 2014; Drijfhout et al., 2014).

1.2 Motivation

The Bohai Sea is the most southern area in the northern hemisphere with sea ice in winter (Ning et al., 2009). The region around the Bohai Sea is an important economic development zone in China. Sea ice as a significant environmental factor in the Bohai Sea must be considered in offshore operations, ports, shipping, and marine fisheries. The monitoring of sea ice distribution and its spatiotemporal evolution plays an important role in maritime activities on the sea ice edge region. In polar and high latitude regions, the extent and outer edge of sea ice as a critical meteorological indicator reflect global climate change, and are essential for long term global sea ice change detection and global climate change monitoring (Wang et al., 2011).

Clearly, it is of vital importance to monitor sea ice spreading and forecast its development to diminish the impact of sea ice formation on the economic and social activities. Remote sensing has become important for monitoring and evaluation of natural disasters combining advanced earth observation with macro-observation, real-time dynamics, and fast imaging abilities. In contrast to high spatial resolution remote sensing data such as Landsat ETM+ and SPOT, which have been widely used in monitoring natural disasters in small-scale regions, moderate-resolution imaging spectroradiometry (MODIS) carried on the EOS series of satellites is suitable for monitoring large-scale disasters with moderate spatial resolution up to 250 m and higher time resolution of up to twice a day (http://modis.gsfc.nasa.gov/). As a new generation of the optical remote sensing instrument, MODIS is well suited for long-term global observation and rapid monitoring of land, biosphere, atmosphere, and oceans (Shi et al., 2002a, b; Salomonson & Appel, 2004; Tschudi et al., 2008). These attributes make it an ideal tool for monitoring and assessing sea ice extent and spreading.

Accurately detecting and describing the subsurface thermal structure of the global oceans is an important aspect of ocean dynamics. Satellite remote sensing provides many useful ocean surface observations at various spatial and temporal scales, but are limited to the surface layers of the ocean (Ali et al., 2004). Since many important ocean processes and features are located well below the sea surface and at considerable depths

(Klemas & Yan, 2014), it is essential to determine the extent to which such surface remote sensing observations can be used to develop information about the ocean's interior (Ali et al., 2004). Subsurface and deeper ocean remote sensing has the ability to derive ocean interior dynamic parameters (especially the thermohaline structure) and enable us to characterize subsurface and deeper ocean processes and features and their implications for the climate variability and change (Klemas & Yan, 2014).

In the previous studies, the strategies for deriving subsurface thermal information from surface parameters are based on either the combination of dynamical models and in situ observations or purely on statistical relationships between the surface and the subsurface parameters. All of the previous statistical approaches were lack of advanced machine learning methods (e.g., Support Vector Machines), which are useful techniques for data classification and regression, and used only one or a few parameters (e.g., SST, SSH, SSS or dynamic height) to synthesize the subsurface thermal structure. Thus, the estimation methods, as well as the accuracy, still have room for improvement.

During recent global warming hiatus, much research based on different scientific perspectives has been carried out to study the hiatus. Some studies found less significant or no hiatus by including polar area (Cowtan & Way, 2014) or excluding oceanic area (Ji et al., 2014) for mean surface temperature calculations. However, by most global measures, the warming hiatus is robustly occurring. The many mechanisms which have been proposed to explain the current hiatus can be generally categorized into external forcings, such as solar radiation, aerosol, and volcanic activities (Lean & Rind, 2009; Santer et al., 2014; Solomon et al., 2011), and internal variabilities, such as ENSO, Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), and deep ocean warming (Kosaka & Xie, 2013; Tung & Zhou, 2013; Wanatabe et al., 2013; England et al., 2014; Meehl et al., 2013). Numerical studies have indicated that the global warming hiatus could be due to increasing heat absorption by the ocean below 700 m depth (Levitus et al., 2012; Balmaseda et al., 2013). Some argue that Pacific plays a more important role (Kosaka & Xie, 2013; England et al., 2014), and other argue that Atlantic and Southern Ocean play a dominant role (Chen & Tung, 2014).

Despite the crucial role of the deeper ocean in the hiatus suggested by these results, understanding of particular mechanisms involved remains inadequate, and the insufficient data coverage and model uncertainties underlying many of these works renders deeper analysis difficult. Most especially, the extreme brevity of the ocean subsurface temperature data coverage (six decades of concerted upper ocean coverage, very sparse coverage to 2000m until the advent of the Argo program in 2001) has been identified as the major obstacle to distinguishing the role the ocean plays in the climate system. As we known, periods of slower and faster trends in GMST aren't unusual, but solving the puzzle of current hiatus is of special importance and within our means. We have unprecedented monitoring of all aspects of the global climate system during the hiatus period, coupled with models and increased knowledge of many of the aspects of climate variability which may be playing a role. Understanding the global warming hiatus is imperative for projection of the future behavior of the changing climate system. The atmospheric, oceanographic and climate community are now confronted with a problem which will require bringing together their knowledge and data for a comprehensive understanding of the mechanisms behind the global warming hiatus.

Chapter 2. Remote sensing of sea ice extent in the frozen Bohai Bay, China during recent surface warming hiatus

2.1 Introduction

Freezing is one of major marine obstacles in China's Bohai Sea, the most southern area in the northern hemisphere with annual sea ice in winter (Ning et al., 2009). The region around the Bohai Bay freezes due to the snow fall and sea ice. This region is an important economic development zone in China. Sea ice as a significant natural obstacle in the Bohai Bay must be considered in offshore operations, ports, shipping, and marine fisheries. The monitoring of sea ice distribution and its spatiotemporal evolution plays an important role in maritime activities in this region.

Many methods are employed to detect sea ice based on different satellite remote sensing data, including threshold segmentation, texture analysis and image classification. Thresholding has been widely used in sea ice detection and classification (Haverkamp et al., 1995). Sea ice has also been detected solely based on simple spectral characteristics of satellite imageries (Su et al., 2012; Su & Wang, 2012). As the imageries have spectral aliasing, the extraction accuracy is affected. Conventional band-threshold segmentation or ratio-threshold segmentation do not eliminate the influence of suspended sediment on sea ice extraction.

Texture analysis is an important method applied to target identification (Barber & Ledrew, 1991; Augusteijn et al., 1995) and image classification (Marceau et al., 1990; Anys & He, 1995; Coburn & Roberts, 2004) because different surface features have different textural features. A gray level co-occurrence matrix (GLCM) is commonly used in describing image textures by studying the spatial correlation characteristics of gray as well as the spatial distribution relationship between pixels. It reflects the spatial relationship between pixels and the characteristics of image elements (Clausi, 2002). GLCM is widely applied in the detection and classification of surface features in remote sensing images (Rajesh et al., 2001; Nyoungui et al., 2002). Sea ice detectability of

MODIS data might be improved by using such GLCM texture analysis. This method determines texture measures for sea ice extraction by analyzing the discrepancy of textural features between sea ice and sea water. Sea ice extent and outer edge could be well recognized by texture segmentation owing to significant differences in texture statistical features between ice and water (Su et al., 2013). Texture features as helpful auxiliary information might significantly improve image classification and feature detection accuracy (Marceau et al., 1990; Augusteijn et al., 1995; Solberg & Jain, 1997; Cai et al., 2010; Zhang et al., 2012).

The surface temperature as basic property is an important feature for sea ice detection in frozen areas because the sea ice surface temperature is lower than that of the sea water surface. This surface temperature difference is crucial in estimating the frozen domain as well as sea ice detection.

Image classification is one of the important methods to extract the target information from remote sensing imagery. The Support Vector Machine (SVM) as one of the most popular machine learning models is very adept at image classification and target recognition (Burges, 1998; Weston & Watkins, 1999; Huang et al., 2002; Chi & Bruzzone, 2007; Gomez-Chova et al., 2008; Su, 2009; Mountrakis et al., 2011; Liu et al., 2013; Maulik & Chakraborty, 2013). Fusing valuable and distinctive image features with spectral features for the SVM classifier might improve image classification accuracy (Waske & van der Linden, 2008; Cai et al., 2010; Zhang et al., 2012).

In this study, we combine the surface temperature (ST) and texture features (TF) with spectral features (SF) for MODIS 500m image classification and sea ice estimation using SVM method in the frozen Bohai Bay. Compared to conventional spectral-based maximum likelihood and SVM methods, the proposed method is superior and more reliable for sea ice detection according to accuracy evaluation based on confusion matrix as demonstrated by selecting test sample points from HJ1B-CCD 30m satellite imagery which we used to validate the detection results with higher spatial resolution.