深度学习在改善海浪遥感以及对海浪数值预报影响的研究与应用进展

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摘要：

海浪是海洋表面最常见的现象。对于海浪准确的观测与预报对于诸如海上航行与渔业等各种海上活动安全具有重要意义。同时海浪对于海气相互作用也具有重要的影响，从而影响气象与气候变化。欧洲与中国基于海洋卫星所开展的海浪遥感观测能够显著地改善了浮标观测空间覆盖不足的局限。本项目的研究目标即基于深度学习方法改进海浪遥感技术及产品，从而进一步提升海浪遥感数据在海浪数值预报中同化的积极效果。本项目相关研究进展如下：

1）原创性的将深度学习技术应用于我国 HY2B 雷达高度计海浪有效波高与海面风速的反演订正。建立深度神经网络（DNN）模型来完成上述订正。该模型使用雷达高度计 sigma0，sigma0 标准差等参数作为输入获得海浪有效波高与海面风速，其系统偏差、均方根误差以及散点指数都有着极大的改善。输入参数的敏感性实验表明 sigma0 标准差对于 HY2B 雷达高度计海浪有效波高与海面风速订正都有着重要作用。

2）中法海洋卫星（CFOSAT）波谱仪（SWIM）在星下点海浪观测之外还能够提供左右两列位置上的海浪方向谱观测，其观测仅能够涵盖波长介于70m到500m之间的海浪。因此我们建立一个DNN模型，使用波谱仪观测到的部分海浪方向谱信息以及最近星下点的观测获得全波长范围内的海浪有效波高，训练真值为与波谱仪交叉时空匹配的雷达高度计海浪有效波高观测。该 DNN 模型获得的波谱仪全波长有效波高精度较高，同化进入海浪数值模式也体现了理想的改善效果。增加同化上述数据的精度高于仅同化星下点观测的精度。

3）我们知道，同化进入数值模式的海浪遥感观测数量对于海浪同化效果有着非常明显的影响。中法海洋卫星同时搭载了波谱仪以及微波散射计，能够获得同步的、精确的海浪观测以及宽刈幅海面风场观测。基于上述同步观测数据，我们原创性的基于 DNN 获得了宽刈幅海浪有效波高产品，将常规的海浪一维观测拓展到了二维，并具有一定宽度的刈幅。该宽刈幅海浪有效波高显著的提高了海浪遥感的空间覆盖率，同时具有较高的精度。同时，一系列的海浪数值同化实验结果表明同化该宽刈幅海浪有效波高数据后相较于仅同化星下点观测能够进一步提高海浪同化效果，充分挖掘了原卫星海浪遥感数据的潜力，实现其数据效果的进一步增益。

总之，基于人工神经网络的深度学习技术在海浪遥感数据精度订正、数据价值挖掘等方面证明了其有效性，基于深度学习获得的海浪遥感产品能够有效的提高遥感数据同化效果。

Progresses of the Research and Application of deep learning for the improvement of Wave Remote Sensing and its Impact on Wave Model Assimilation

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Surface waves are one of the most common phenomena in the oceans. The accurate monitoring and forecasting of waves are critical for guaranteeing the safety of all kinds of marine activities, such as sailing and fishing, and are also of great importance to understanding air-sea interactions, which significantly impact weather and climate projections. Remotely sensed ocean waves from European and Chinese space missions have significantly supplemented the insufficient coverage of traditional wave observations such as buoys. The objectives of this program are improving the wave remote sensing and enhancing the positive effect of assimilation. The progresses are listed below:

1). A deep learning technique is novelly applied for the calibration of Chinese HY2B SWH and wind speed. Deep neural network (DNN) is built and trained to correct SWH and wind speed by using input from parameters provided by the altimeter such as sigma0, sigma0 standard deviation (STD). The results based on DNN show a significant reduction of the bias, root mean square error (RMSE), and scatter index (SI) for both SWH and wind speed. Several DNN schemes based on different combination of input parameters have been examined in order to obtain the best model for the calibration. The analysis reveals that sigma0 STD is a key parameter for the calibration of HY2B SWH and wind speed.

2). In addition to the nadir significant wave height (SWH), the Surface Waves

Investigation and Monitoring (SWIM) onboard Chinese-French Oceanic SATellite (CFOSAT) provides two additional columns of wave spectra observations within wavelengths from 70 m to 500 m. A model based on a DNN is developed to retrieve the total SWH from the partially wave spectra observed by SWIM. The DNN model uses the parameters from both the SWIM spectra and the nearest nadir as the inputs, and the DNN is trained on the SWH from cross-matched altimeter observations. The DNN-based acquisition of the SWH is verified to achieve a high accuracy. A set of assimilation experiments are performed based on MFWAM and show promising results. Compared to the assimilation of SWIM nadir SWHs only, the addition of the newly obtained SWIM SWH notably enhances the positive impacts of assimilation, not only proving the effectiveness and accuracy of the DNN model but also demonstrating the unique potential of SWIM in wave assimilation.

3). The accuracy of a wave model can be improved by assimilating an adequate number of remotely sensed wave heights. The SWIM and Scatterometer (SCAT) instruments onboard CFOSAT provide simultaneous observations of waves and wide swath wind fields. Based on these synchronous observations, a method for retrieving the SWH over an extended swath is developed using the DNN approach. With the combination of observations from both SWIM and SCAT, the SWH estimates achieve significantly increased spatial coverage and promising accuracy. As evidenced by the assessments of assimilation experiments, the assimilation of this ‘wide swath SWH’ achieves an equivalent or better accuracy than the assimilation of the traditional nadir SWH alone and enhances the positive impact when assimilated with the nadir SWH.

Overall, deep learning, which is based on artificial neural networks, has proved its efficiency and effectiveness in improving the European and Chinese wave remote sensing missions, and obtaining a better assimilation effect in wave numerical model simulations.