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Progress in Marine Meteorology Studies in China during 1999–2002

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ABSTRACT

The progresses of marine meteorology studies achieved in China during the four year period from 1999 to 2002 are summarized in six directions: air-sea flux, marine meteorology in high latitudes, marine disasters, connection between ocean and weather/climate in China, remote sensing applications and new methodologies in marine meteorology. Compared to the previous ones, these studies adopted much more first-hand datasets, and more scientific issues were involved. As an exciting remark, there were so many contributions done by the young scientists. A brief statement about the research strategy of marine meteorology in China for the coming years is also given.

Key words: marine meteorology, China, field observation, marine disaster, remote sensing application

1. Introduction

Marine meteorology has developed greatly in the past four years in China. Several in-situ experiments related with marine meteorology saw many successful progresses carried out by Chinese scientists, for example, the South China Sea Monsoon Experiment (SCSMEX), the South China Heavy Rain Experiment, the Chinese First Investigation of the Arctic, the Comprehensive Survey of the Nansha Islands, and so on. These experiments enriched the data bank required by marine meteorology research, and the results based on observational data came forth out of the experiments. In our review, a great proportion of papers belong to this class, which are based on recent observational data.

In order to conveniently document the progresses of marine meteorology studies in China during the past four years, we divide the content into six aspects in this paper. The first aspect is observation and parameterization of the air-sea flux. The main advances were air-sea flux observation in the South China Sea (SCS), the tropical Pacific, and other oceanic regions, and improved parameterization of the air-sea flux. The second aspect is sea ice, polar and high latitude marine meteorology. This includes the interannual and interdecadal variability of sea ice in the Arctic and Antarctic areas, sea ice thermodynamics process and mechanism analysis in Chinese seas, and sea ice model validation. The third aspect is marine meteorological disasters. The main points are climate dynamics associated with tropical cyclones in the Northwest Pacific, tropical cyclones influencing China, the observation and simulation of typhoon storm surges, as well as the prevention and reduction of marine disasters. The fourth aspect is the influence of the sea surface temperature (SST) anomaly on weather and climate over China. The highlights are the relationship between weather and climate over China and SST in the tropics, predictability significance of the prophase SSTs, and so on. The fifth aspect is the interpretation of the development of remote sensing research in marine meteorology. The key is the contribution of Chinese scholars to remote sensing of SST, sea surface wind field, and wind waves. The sixth and final aspect is the reporting of data analysis achievement in sea temperature analysis, data assimilation, and its application.

2. Observation and parameterization of air-sea fluxes

Atmospheric circulation variability is driven di-

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rectly by heat fluxes of the earth surface, so it is very important to describe these heat fluxes exactly in the atmospheric models. The sea surface is the widest underlying part of the earth, so much more attention was paid to sea surface heat fluxes. In some key areas, such as the western Pacific warm pool, the eastern Pacific cool tongue, the ITCZ (Intertropical Convergence Zone), and the trade wind zone, the exact estimation of sea surface heat fluxes over the area is very important. The changes of fluxes over these areas were regarded as the reasons causing the ENSO (El Niño and Southern Oscillation) evolution, which is the strongest climate signal on the earth.

2.1 *Observational progresses in the SCS*

Researches on air-sea fluxes of momentum, heat, and moisture over the SCS have developed rapidly in recent years. Now the local observations in the SCS had been well developed. The SCSMEX and the scientific investigation in the Nansha Islands in the National Ninth Five-Year Plan, offered trustworthy data for studies on air-sea fluxes of momentum, heat, and moisture in the SCS. Xu and Qu (2000) calculated the turbulent flux transfer during the different weather conditions in winter 1997. The results showed that all the momentum flux from atmosphere to ocean, and sensible and latent heat fluxes from ocean to atmosphere, during the rainfall period were obviously greater than those during other weather periods. Wu et al. (2001b) studied the air-sea heat exchange under typhoons over the SCS. The main contribution to fluxes was from latent heat flux. When El Niño occurred, SST in the SCS became warmer, whereas the air-sea heat exchange became weaker. Gao et al. (2000b) calculated the aerodynamic roughness length and the neutral drag coefficient both on the smooth and rough sea surfaces over the Nansha Islands in September 1994. The relationship of aerodynamic roughness lengths, drag coefficients, and bulk exchange coefficients with wind speed were also analyzed. Yan et al. (2000) detected the turbulence structure and flux transfer at the sea surface during the onset of the SCS monsoon in 1998. Intensities of the turbulence were estimated. An expression for the friction velocity was also provided by them.

2.2 *Parameterization of the fluxes*

To a certain degree, the performance of modeling and prediction depends on the parameterization skill of air-sea fluxes in oceanic and atmospheric models. The study on the influence of mesoscale enhancement on subgrid-scale sea surface fluxes of a large-scale model by Zhang et al. (2001) indicated that the parameterization method of the mesoscale enhancement of sea surface fluxes must take the grid scale of the model into account. Zhao and Zeng (2000) noticed some problems in the computation of moisture and heat fluxes at the formula for surface for atmospheric models. They suggested a new flux-profile relationship, which was more reasonable theoretically, in which the effect of moisture on the Monin-Obukhov parameter was considered, and a scalar roughness for virtual potential temperature was also introduced. Zhou et al. (2001) designed a coupled method in a climate model to deal with air-sea flux exchange and successfully tested it by using the Global-Ocean-Atmosphere-Land system model developed at the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG).

Air-sea exchange is a critical process of the air-sea interaction. Qian and Zhou (2001) analyzed temporal variations and geographical distributions of air-sea sensible and latent fluxes over the Pacific by using products from the Goddard Earth Observing System and four-dimensional Data Assimilation System. The results showed that heat flux over the northwestern Pacific varied obviously with the seasons, and the values of sensible heat fluxes were often very small except over the ocean area north of 20°N, and there was no extremum region at all. Regarding the impacts of the SST diurnal cycle on the intraseasonal variation of surface heat flux over the western Pacific warm pool, Li et al. (2001) developed a parameterization scheme of the diurnal cycle of SST. The comparison was performed by integrations of the National Center for Atmospheric Research (NCAR) Community Climate Model, forced by observed weekly SSTs with and without the diurnal cycle of SST, respectively.

3. Marine meteorology in polar and high latitudes

Sea ice, as an important component of the global climate system, affects atmospheric and oceanic circulations directly by interaction with airflows and currents. There exist notable correlations in different spatial scales and timescales between sea ice and atmosphere, and sea ice and ocean, implying the importance of the ice-air-sea interaction in affecting climate in local areas, semi-globally and even on global scales. In the polar region and high latitudes, ice and ocean, as the underlying surfaces of the atmosphere, play a dominant role in the energy budget and hydrological cycle of the climate system. The high albedo of sea ice, decreasing the absorption energy of the climate system, is the main cause of polar region cooling.

3.1 *Sea ice variations*

Sea ice offshore of China has a significant interannual variability. The relationship between the Bohai, northern Yellow sea ice, and the climate change were investigated (Bai et al., 2001). The results suggested that the continuous diminishing sea ice in the Bohai in the 1990s coincided with the global warming trend. The interannual variation in the Bohai and northern Yellow sea ice situation was relevant to the El Niño phenomenon and the solar activity.

Several scientists addressed the spatial and temporal evolution of sea ice in the Arctic and Antarctic. The monthly and annual characteristics of SST in the tropical western Pacific and Indian Oceans was analyzed using COADS (Comprehensive Ocean Atmosphere Data Set), together with their relationship with ENSO and the Antarctic sea ice. The analysis suggested that SST in the tropical western Pacific and Indian Oceans and the Antarctic sea ice area have a close relationship, and the outstanding correlation showed that there is a 16-month SST lagging the coverage of Antarctic sea ice (Chen and Qin, 2000). There exists a robust interannual oscillation of sea ice in the Arctic and Antarctic (Zhao et al., 2000b). The Antarctic sea ice shows coherent characteristics of interannual variation in summer, but quite strong regional characteristics in autumn, winter, and spring. The interannual anomalies of Arctic sea ice occur in different areas in cold and warm seasons, respectively. Using 1953–1990 sea ice datasets, Wu et al. (1999) pointed out that the sea ice coverage variation in the Kara Sea and the Barents Sea in winter might exert an influence on SST variability in the North Pacific in the succeding periods. Sea ice variability in the Barents, Greenland, Baffin Bay, Davis Strait, and Bering Seas in winter and spring was both interannual and interdecadal (Wu et al., 2000a). The spring and winter sea ice in the Kara and Barents Seas are out of phase with the change in sea ice in the Bering Sea. Sea ice in the Greenland, Kara, and Barents Seas possess significant variability of a 12-year and 10-year period, respectively. Wu et al. (2001a) simulated the impact of the Arctic sea ice thickness and area on climate change of the East Asian regions using the LASG two-level GCM. The results showed that the variation of sea ice thickness could motivate the propagation of planetary waves that spanned Eurasia, and could also affect convection in the low latitudes.

Numerical modeling is a powerful tool to gain insight into the thermodynamics associated with sea ice. Liu et al. (2000) improved the ice-ocean thermal coupling scheme, applied in a global ice-ocean coupled model. A one-dimensional sea ice thermal model can better reflect the sea ice variation trend in the vertical direction, but it cannot embody the sea ice condensation increase in velocity as well (Zhang et al., 2000).

3.2 *Climate implication of polar sea ice*

The relationship between Arctic sea ice and precipitation in North China was studied. It was disclosed that the strong signal phenomenon of Arctic sea ice appeared before climate anomaly on the seasonal scales in the regions of China and in the Northern Hemisphere. As such, the dynamics features of the impact of the Arctic sea ice strong signal area on the drought in North China in summer were also analyzed (Bai et al., 2000). As an important part of the underlying surface, the cryosphere is in a process of continuous interaction with the atmosphere. It was shown that the Arctic sea-ice strong signal region was highly correlated with the summer precipitation in North China. The mechanism of how the Arctic sea-ice would affect the Northern Hemisphere summer circulation and the flood/drought in North China was put forward, namely how the Arctic strong signal region might affect the abnormal precipitation of North China.

3.3 *Polar lows*

Fu et al. (1998a, b) studied a typical polar low event that occurred on 26 February 1996 over the Japan Sea. GMS-5 infrared satellite data as well as JANAL (Japan objective ANALysis) data were employed to document the large-scale environment and the structure of this polar low. Examination of the satellite data showed that the whole life history of this polar low can be classified into four stages: the initial, developing, mature stage, and dissipated stage. The spatial structure of the large scale environmental conditions are characterized by a strong baroclinic zone at a low level. The observational studies, the studies of dynamical mechanisms, and the numerical modeling of polar lows occurring over the high latitude oceans were reviewed by Fu et al. (1999). The polar lows became a new research subject of marine meteorology in China, and further research is still ongoing.

4. Marine meteorological disasters

Marine meteorological disasters generally include tropical cyclones (so far including typhoons), marine gales, marine fog, marine severe convective storms, storm surges, sea ice, sea waves, tsunamis and so on. They mainly obstruct the civil activity over the sea and in the coastal belts; as well some of them endanger the safety of the economy and can destroy life and property from the seashore to large inland regions. All of them generally have the background of marine environmental calamities caused by severe weather systems. Because of the difficulties of carrying out in-situ measurements, the mechanism of marine meteorological disasters has not been studied fully, and this makes marine meteorological disasters an austere challenge in reducing and preventing the general disasters. The Northwest Pacific is the most frequent and strongest region of global tropical storm activity and China is one of the most seriously affected countries by typhoons along the seashore of the Northwest Pacific. About 80–100 tropical cyclones occur every year globally and they have a great impact on human life. The loss caused by tropical cyclones is the severest and accounts for 64% of the death caused by all natural disasters. According to the statistics, 15–20 thousand persons have died in the calamity of tropical cyclones, and the global economical loss adds up to 6–7 billion RMB Yuan annually.

4.1 *Cyclones and tropical storms*

The response of the ocean to typhoon (tropical storm) processes has not been so well monitored due to the high expense required. People have another option, that is, to simulate or predict typhoon's impact by models. Using a numerical model, Su et al. (2001) quantitatively analyzed the factors that could cause SST change during a typhoon process in the Yellow Sea and Bohai Sea. The rate of SST change caused by different factors in the typhoon center and its adjacent points were given as well. Yang (2001) examined the degree of disasters (disaster classification, disaster frequency, occurrence over return period) caused by typhoon landfall along the long coastal line from the Bay of the Bohai Sea to Guangxi, South China, and pointed out the possibility of addressing the destruction of strong typhoons using the Poisson distribution. Xie et al. (2001a) studied the diagnostic model of typhoon surface wind in the coastal and estuary regions. The large domain wind fields and the initial wind fields of the mesoscale dynamic diagnostic model were obtained through nesting the typhoon model with that of the NCAR objective analysis. At the same time, through a nudging assimilation scheme combined with real data to rectify the diagnostic wind field, one might obtain sea surface wind fields in these regions. Gao et al. (2001b) tested the 24-hour prediction of sea surface winds in the Bohai Sea with the initial field provided by an objective analysis of the T106 model grid data and the observation data in the upper air and the ground layer, as well as the time-dependent boundary condition provided by the T106 model every 6 hours.

The characteristics of cyclones over the sea are quick to develop and therefore are difficult to predict. Qian et al. (2001) objectively classified the disaster grade to manifest the degrees of destruction. In order to validate the method, evaluation by the independent Suffir-Simpson data of tropical cyclone disasters was also done. Lin and Zhan (2000) analyzed the impact of SST in the equatorial eastern Pacific on an extratropical cyclone, for example, over East Asia and the Northwest Pacific. The corresponding relationship was preferential that a strong extratropical cyclone was excessive in an El Niño year or succeding year. But when the subtropical high was slightly higher than normal, the extratropical cyclones were less. Zhang et al. (2000) tested the dynamical reason of explosive cyclones in winter and found that the occurrence and development of explosive cyclones was due to the southern invasion of abnormal vorticity below the stratosphere and downward propagation of a perturbation in the troposphere, hinting an upper-lower coupled development. Ma et al. (2002) addressed the impact of atmospheric baroclinicity, such as the enhanced vertical shear of wind, to the initial developing of Jianghuai cyclones. For a complete summary of the climatology for these extratropical cyclones, one may refer to the work of Qin et al. (2002).

4.2 *Storm surges and sea fog*

Storm surges are one form of marine dynamical disasters which bring great destruction. Several studies have demonstrated the important role of an enforced and accurate prediction of disasters to reduce and prevent marine disasters. Yu et al. (2000) developed a numerical model for extratropical storm surges with a spherical coordinate. Simulations showed that the numerical modeling of extratropical surges was practical as long as the forcing wind was accurate. The simulation by Wang et al. (2001e) showed that the computation domain of the sea would seriously affect the modeled process of storm surges in an enclosed or semi-enclosed sea, and a satisfactory result would be obtained only when the calculation field covered both the Bohai and Yellow Seas. Using a two-dimensional barotropic shallow water model and nesting computation skill, Zhao et al. (2000a) simulated storm surges over 20 consecutive years in the Chengbei area and adjacent regions in the Bohai Sea and did long-term predication of return period set-up values induced by storm surges. Zhou and Sun (2000) simulated storm surges caused jointly by Typhoon 8114 and the astronomical tide using a two-dimensional numerical model to study the nonlinear interaction between storm surges and astronomical tides in the sea area off the Yangtze River mouth. Li et al. (2000a) introduced the disaster outline of southern Fujian Province caused by Typhoon 9914, and analyzed the characteristics of typhoons and storm surges there.

Sea fog is another marine meteorological phenomena affecting sea activity greatly. Xie et al. (2001c) found that various kinds of sea fogs can be formed, such as advection fog, radiation fog, and evaporation fog in the Arctic, most of which were covered with ice or was mixed with ice. The reason why there were many kinds of fog types in the Arctic Ocean was the complicated cushion and consequent sea-air interaction caused by sea ice distribution and its unique physical characteristics. Using the East Asian daily 08Z surface synoptic charts from 1980–1997, Li and Wang (2000) induced and analyzed four kinds of synoptic types that could form fog in the Taiwan Strait region (20°–27°N, 115°–125°E). They are the cold advection prevailing pattern, warm advection prevailing pattern, homogeneous pressure field pattern, and typhoon outer region pattern.

5. Influence of ocean on weather and climate over China

As early as the 1950s, Chinese scientists had noticed the relationship between SSTA (SST anomalies) in the Northwest Pacific and consequent drought and flood in the Yangtze River region. After that, many people dedicated themselves to search for sea areas of previous SSTA, which were closely connected with climate in China, including the spring equatorial cool water zone, the Arabian Sea, the Indian Ocean, the SCS, Kuroshio, the western Pacific warm pool, and the equatorial eastern Pacific, etc. Recently, many researchers have related SST or sea ice with anomalous atmospheric circulation and achieved the atmospheric teleconnection wavetrain, which was connected with SSTA preceding the Chinese summer climate anomaly. Thus they disclosed the detailed processes that the preceding SSTA affected the Chinese climate anomaly by a way of modifying the atmospheric circulation. It was pointed out that SSTA in the western Pacific warm pool would cause a teleconnection wavetrain and further influence summer rainfall in the middle and lower reaches of the Yangtze River. The atmospheric circulation anomaly caused by the propogation of a quasi-stationary planetary wave would cause an atmospheric circulation anomaly in other areas.

5.1 *ENSO-related cases*

There is a rather complex relationship between summer precipitation over China and SST in the Pacific. Using 50-year observational data, Ge (2000) diagnosed summer precipitation in China and SST in the Pacific and discovered both characterized a decadal variability. Sensitive numerical experiments were carried out when sea temperature in the Pacific was of a warm background in order to search for a dynamic explanation. Chen (2000) examined the summer drought/flood events in China under the conditions of the winter-strengthened patterns and winter-weakened patterns of the El Niño and La Niña events. A physical concept pattern was proposed to interpret the summer rainfall patterns over China, associated with different patterns of El Niño and La Niña in winter. Lin and He (2000) investigated the relationship between the Pacific SSTA pattern and the East Asian atmosphere circulation and rainfall in the middle and lower reaches of the Yangtze River. The numerical experiments further confirmed that rainfall in the middle and lower reaches of the Yangtze River was not only related to SSTA in the tropics but also to that in the mid-latitude Pacific. Li and Shou (2000) considered that the eastern equatorial Pacific SST was the factor of summer drought/flood in the Huaihe River region. The summer precipitation over the Yangtze River and the Yellow River valleys was greater than normal when El Niño warming occurred in autumn or winter, but less when ENSO developed in spring or summer. A high correlation between the preceding and simultaneous SST in the northern Pacific and spring rainfall in northwestern China was detected objectively (Wang et al., 2001a). Such forecast significance of some high correlation areas was discussed in terms of the leading months. Sun et al. (2000) suggested an index of land-sea thermal difference (ILSTD). The index can reflect the interannual variation of summer rainfall anomaly over East China, especially in Northeast China, and the Huaihe River valley and the middle and lower reaches of the Yangtze River. In the years of strong ILSTD, the rainfall belt was mainly located over the north part of China, and an obvious drought emerged in the Huaihe River valleys and the middle and lower reaches of the Yangtze River. Zhu et al. (2000) investigated the barotropic and baroclinic components of the 850-hPa u field to look for a possible mechanism causing the effect of the SSTA in the preceding March over (42.5°–52.5°N, 170°E–170°W) on the summer rainfall in East China. The results showed that SSTA in March affected the 850-hPa baroclinic wavetrain of the same season. The baroclinic wavetrain in March could affect the baroclinic wavetrain in summer, which at last could change the summer rainfall in East China.

5.2 *Impact from other ocean basins*

Chinese scientists also noticed the possible impact on East Asian climate from other oceans, for example, the Atlantic Ocean. Meiyu onset dates (MOD) were significantly related to the atmospheric features in the preceding winter. With strong North Atlantic Oscillation (NAO), the Meiyu onset was early (Xu et al., 2001). There existed a pronounced correlation between the MOD and SST over the North Atlantic in the preceding winter to spring, with positive SST anomalies for earlier Meiyu onset and negative anomalies for later Meiyu onset.

Impacts of SSTA in the Indian Ocean on weather and climate in China have become greatly attractive to researchers since the Indian Dipole was reported. The numerical simulation experiments showed that SSTA in the Indian Ocean posed a significant influence on the distribution of precipitation anomalies in China during El Niño. Yan and Xiao (2000) indicated that the warmer (colder) SSTA in the equatorial Indian Ocean would result in a wavetrain, which was similar to the teleconnection patterns PNA (Pacific and North American) and EAP (East Asia/Pacific) in middle and high latitude regions. With the warmer (colder) SSTA forcing, the Asian summer monsoon would burst later (earlier) and withdraw earlier (later) than normal, and it would last shorter (longer) and its intensity would be weaker (stronger) than normal. Li and Ding (2002) found that a negative correlation existed between summer rainfall in North China and SSTA in the Indian Ocean areas, which was close to the east coast of Africa. The SSTA pattern with warm west and cold east in the Indian Ocean would make Indo-China drier and precipitation over northern China reduced, but would make the precipitation over Southwest and South China increased (Xiao et al., 2000).

Waters which affect East Asian weather and climate are varied with interannual variability of the ocean-atmosphere system. Several studies checked out the relationship between atmospheric circulation in East Asia and SST in the SCS and its vicinity. Gao et al. (2000a) classified the features of atmospheric circulation and SST with reference to anomalous occurrence of the tropical cyclones in Fujian during 1951–1996. Mao et al. (2000) reported that SST over the SCS, Pacific, and Indian Ocean and their variations could all influence the onset of the summer monsoon over the SCS. Wang et al. (2001c) did numerical experiments on the regional atmospheric circulation's response to SST anomalies in the SCS and its vicinity. When there were cold SST anomalies in the SCS and the Bay of Bengal and warm anomalies in the western tropical Pacific Ocean, there was an anomalous northeasterly over the SCS in February and March. Moreover, an anomalous anti-cyclonic circulation (AAC) was generated over the Philippines in summer. The AAC′s low frequency variability would result in a coherent low frequency activity in the East Asian atmospheric circulation by way of teleconnection. Ren and Qian (2000) found that there was an apparent negative correlation between latent heat flux over the northern SCS in the preceding winter and the simultaneous summer precipitation in South China and its coastal regions. A strong positive correlation in spring was found between latent heat fluxes over the middle SCS and the precipitation in the area from the south of the Yangtze River to South China coastal regions. Qian and Chen (2001) searched for the relationship between monsoon intensity and sea level anomalies for the mouth of the Pearl River around the occurrences of El Niño in the past 45 years. The results showed that the mean wind speed was larger than normal in the preceding winter and monthly mean speed was generally higher than normal in the current year of El Niño events, while the monthly mean sea level was lower than normal.

6. Remote sensing in marine meteorology

The physical oceanographic phenomena with the basin scales are a large rescarch concern. But the investigated region at present is only just a part of the whole ocean, so all of the knowledge on these events has not been well revealed yet. In conventional oceanographic surveys, which were influenced by many factor and especially by limited money, the vast sea area could not be explored entirely at the same time. Therefore, the remote sensing of marine meteorology is superior to explore such a vast area versus the conventional surveys.

6.1 *Surface wind*

Microwave remote sensing applied in marine meteorology provides accurate retrieval for sea surface wind and ocean waves. He (2000) discussed the possibility to measure ocean currents and bottom topography, and provided the method to detect ocean waves, sea surface wind, surface current, bottom topography, and internal waves, by using the microwave scatter principles over the sea and SAR (Synthetic Aperture Radar) missions. Wang et al. (2001d) found the spatial and temporal features of wind and wave fields in the SCS by using EOF analysis on sea surface wind and wave fields deduced by Topex/Poseidon space-based altimeter data. The result showed an exact relationship between the wind field and the wave field in the SCS. Xie et al. (2001b) found that the remote sensing data had finer resolution and more reasonable values by using remote sensing (ERS1 and ERS2) data, COADS data, and Hellerman & Rosenstin objective analysis data to analyze sea surface stress in the SCS. Therefore, they suggested choosing remote sensing data in the study of climatologic features of the distribution of wind stress and its seasonal variability in the SCS, especially for the purpose of studying small and middle scale eddies. Analyzing the remote sensing data by the Geosat altimeter between 1987 and 1988, Qi and Shi (1999) indicated the distribution of monthly sea surface wind speed and significant wave height in the SCS, and the annual cycle of wind and wave fields along the NE–SW direction. In their paper, it was intercompared with wind and waves based on buoy data. Pang and Sun (2000) studied primarily microwave radiation theory and data procession, based on in situ measurement by microwave radiation. Also, a relationship was shown to exist among many kinds of conditional and radiometer parameters and the microwave spectrum over the sea. Fang and Chen (2001) developed a marine geographical information system (MGIS) for predicting the global extreme sea surface wind speeds. It could be used to model the global wind system, estimate its extreme values, and visualize the predicted results. The significance of estimating the global extreme wind speed and the importance of using MGIS in the analysis process were addressed. A statistical model for estimating global extreme sea surface wind speed was proposed.

The sea surface wind vector can be measured by imaging radar on space aircraft. The SAR images from April 1994, taken from imaging radar on aircraft over the SCS, were analyzed by Wang and Pan (2000). The wind direction was taken from the SAR image spectrum by using SIR-C data. And the wind speed was retrieved from the C-band radar backscatter by using an empirical model.

6.2 *Surface temperature and topography*

SST derived from the infrared remote sensing observation not only provides the thermal situation of the ocean, but also implies information on the oceanic currents. Xu (2001) revealed the oceanic phenomena over the SCS by using the AVHRR (Advanced Very High Resolution Radiometer) images covering the South China Sea in the period of 1989–1993 and in situ measurement data over the northeastern SCS in March 1992. The distribution of SSTs derived from satellite images almost coincided with the in situ measurement. The retrieval method for obtaining orbiting meteorological and operational satellite product SST and its verified accuracy were presented by Wang (2001) using the data based on ships in each month of the four seasons in 1996 to verify the accuracy of SST. The mean difference was –0.6°C; the root-mean-square difference was 1.5°C. The difference between the Pathfinder SST and in-situ data in the East China Sea (Gao et al., 2001a) showed that the PESST data coincided with the in-situ measurement. 67.6% of all analyzed data differences were less than or equal to 0.5°C, and the root-mean-square difference was 0.61.

Remote sensing analysis of dynamic oceanic processing: Liu et al. (2002) analyzed the tides deduced from Topex/Poseidon altimeter data over the SCS by using the comparing difference method. The synthetic geostrophic current fields were derived from the mean sea level and sea level height anomalies. It was found that the surface geostrophic current in the SCS was generally cyclonic. The western intensification of surface currents in autumn and winter was obvious. He et al. (2001) found that the trajectories of four Agros drifting buoys over the SCS fit the tracks of oceanic basin scale circulation in each season, and showed their mesoscale features in the west of the Philippines, the outer sea off Vietnam, and the central part of the SCS, respectively. These mesoscale eddies were validated accurately by the sea level height anomalies from Topex remote sensing data at the same time. Ji et al. (2002) suggested one method to examine the mesoscale eddies from remote sensing images over the sea. The results showed that the mature vortexes, which had obvious features in shape, were inspected.

7. New methodology in marine meteorology

Any progress in methodology in marine meteorology will lead to successful advances in experimental and operational applications. Recently, oceanic prediction has attracted much attention with a revolution in data collection and great improvements in data assimilation in atmospheric and oceanic models.

7.1 *Variational data assimilation*

Theoretical studies on data assimilation in marine meteorology have provided a reasonable fundament for us to adopt the new techniques in this field. As an example, the derivation of the First Order Adjoint (FOA) and Second Order Adjoint (SOA) models of the shallow water equations are given in detail by Han et al. (2000a), where they obtained the Hesse matrix of the SOA, which improves a previous SOA theory. In order to provide a more accurate initial field for numerical prediction of SST, the adjoint method was applied by Han (2000b) to assimilate sea temperature observations into a one-dimensional model. By a method of a discrete adjoint operator in data assimilation for prediction of the vertical distribution of temperature, He et al. (2000) obtained an accurate initial temperature field for numerical prediction. Wang et al. (2000a) carried out an objective analysis method, which can be used to improve oceanic observation schemes optimally depending on variational data assimilation.

Prospects of marine prediction seem exciting due to the many applications of data assimilation in marine meteorology. Prediction of the annual occurrence of tropical cyclones using the products of a hybrid air-sea coupled model was done by Li et al. (2000b) by applying a four-dimensional variational assimilation system regarding optimization of the initial field for the predicting integration. Thus, the prediction accuracy of the interannual SSTA in the tropics was improved. Duan et al. (2000) applied the four-dimensional variational data assimilation system of the Zebiak-Cane model to predict ENSO. Compared with the observational result, the forecasting results derived from this assimilation system in which the fields of January 1997 were reproduced, agree well with it. In an assimilation experiment of blending Topex altimeter data in the SCS, Wang et al. (2001b) compared the control run result without assimilation and that with the assimilating run. They found out that blending TOPEX altimeter data could reasonably modify the large-scale circulation in the SCS, such as the dynamic process relevant to the impact on the northeastern SCS caused by the intrusion of Kuroshio. Lü (2001) applied a variational optimal technique for assimilating both meteorological and oceanographic (surface and current) observations into an oceanic Ekman Layer model, through which the unknown condition (such as the wind stress drag coefficient) and the unknown vertical eddy viscosity are deduced simultaneously by the method. Chen et al. (2001) used the Princeton Ocean Model to assimilate observation data (including AXBT (Air-dropped Expendable Bathythermograph) and multi-channel SST derived from satellites) from the SCS in May 1995. The results showed that the simulated temperature and current field were improved greatly. In order to improve the prediction of tidal information over the continental shelf, Han et al. (2001) used a variational assimilation method in the Yellow Sea and East China Sea by incorporating the data from tide stations with and without Topex/Poseidon altimeter data.

7.2 *Objective analysis methodology*

In the past four years we have seen several new techniques for sea temperature analysis and forecasting that were proposed in China, which provide insight for further applications in marine meteorology. Wei et al. (2001) provided a method to detect the embedded frequencies in a chaotic system to analyze ocean data. They detected the embedded periods of the equatorial daily SST time series and the nine-point running mean monthly air temperature of Qingdao, using the frequency spectrum and the probability of points in a reconstructed phase space. The application of a localized nonlinear direct forecasting method to detect ocean chaos and noise (Wei et al., 2000) gave evidence that this method is better than a kind of general spectral analysis in detecting chaos and noise in the SST time series. In a regressive filter objective analysis of SST fields undertaken by Wang et al. (2000b), a regressive filter was used to deal with scale-varying and heterogeneous SST data. By adjusting several key parameters, they obtained the SST fields at a fine resolution. Using a natural oscillator equation, Cao et al. (2000) obtained an inverse time-lag natural-oscillator equation, which can describe the quasi-nonlinear feature of SST evolution in the eastern tropical Pacific. Jiang and Wu (2001) exmined the Tropical Ocean-Global Atmosphere-Tropic Atmosphere Ocean array SST data of the 53 buoys moored in the tropical Pacific in winter 1994 to determine whether ocean chaotic characteristics exist in the tropical Pacific. They found that the underlying system of the eastern and western Pacific is always chaotic, but the reasons for the chaos present in the two regions may be different. Ren and Zhou (2001) applied an analogue model, which is suitable for carrying out a similarity forecast for a time series, to the Niño-3 SST anomaly, an important index for ENSO monitoring. The maximum leading period of effective prediction is 8 months, and the similarity forecast has quite a good ability for predicting the turning-point events.

8. Remarks

As seen from the above, a large number of papers have been published in the past four years by the Chinese oceanographic and meteorological community in marine meteorology studies. These great efforts were made in several aspects, for example, air-sea flux, marine meteorology in high latitudes, marine disasters, the connection between ocean and weather/climate in China, relevant remote sensing applications, as well as in new methodologies in this field. The Chinese scientists should aim at the international development tendency of meteorology, and probe into the predominant development domains of marine meteorology in China in the days to come. In order to keep a solid connection with the international programs such as CLIVAR, GOOS (Global Ocean Observation System), GCOS

(Global Climate Observation System), etc., Chinese scientists should pay more attention to these diagnostic studies on the fingerprints of ENSO, PDO (Pacific Decadal Oscillation), and the Indian dipole mode, as well as the NAO impact on China. The most important underlying purpose is to absorb all the data and scientific achievements shared within these international programs into the ongoing improvement of weather and climate prediction skills in China. Most people agree that the SCS will be the next hot spot in marine meteorological research both domestically and internationally. There is a great lack of observations as far as the exact influence of the SCS on the East Asian climate is concerned. Note that there is a proxy climate index such as coral records in the SCS, which are able to provide long term variations on the century to millennium time scales. Thus, the relative role of local versus remote forcing on the SCS can be addressed.

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