Progress of Large-Scale Air-Sea Interaction Studies in China

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ABSTRACT

This paper summarizes the progress of large-scale air-sea interaction studies that has been achieved in China in the four-year period from July 1998 to July 2002, including seven aspects in the area of the air-sea interaction, namely air-sea interaction related to the tropical Pacific Ocean, monsoon-related air-sea interaction, air-sea interaction in the north Pacific Ocean, air-sea interaction in the Indian Ocean, air-sea interactions in the global oceans, field experiments, and oceanic cruise surveys. However more attention has been paid to the first and the second aspects because a large number of papers in the reference literature for preparing and organizing this paper are concentrated in the tropical Pacific Ocean, such as the ENSO process with its climatic effects and dynamics, and the monsoon-related air-sea interaction. The literature also involves various phenomena with their different time and spatial scales such as intraseasonal, annual, interannual, and interdecadal variabilities in the atmosphere/ocean interaction system, reflecting the contemporary themes in the four-year period at the beginning of an era from the post-TOGA to CLIVAR studies. Apparently, it is a difficult task to summarize the great progress in this area, as it is extracted from a large quantity of literature, although the authors tried very hard.

Key words: air-sea interaction, various time and spatial scales, atmosphere/ocean variability, climatic abnormality

1. Introduction

Study of the air-sea interaction is an important scientific endeavor in China. The research activities of Chinese scientists are vigorous and productive in this area. A large number of scientists have participated in international programs related to large scale air-sea interaction studies such as the Tropical Ocean and Global Atmosphere Program (TOGA), the Coupled Ocean-Atmosphere Response Experiment (COARE), the World Ocean Circulation Experiment (WOCE), the study of Climate Variability and Predictability (CLIVAR), and others for many years, and have organized domestic projects funded by the National Natural Science Foundation of China, the Chinese Academy of Sciences, the China Meteorological Administration, the State Oceanic Administration of China, and other agencies. This report is intended to briefly introduce the progress in the large-scale air-sea interaction studies made in China according to the literature published by Chinese scientists in the four-year period from July 1998 to July 2002.

2. The Air-sea interaction studies related to the tropical Pacific Ocean

The tropical Pacific Ocean is the tropical sea area nearest to China, where oceanic abnormality is closely associated with the climatic variability in East Asia including China. Therefore the tropical Pacific Ocean has drawn much attention of Chinese oceanographers and meteorologists for a long time. The research activities can be divided into the following aspects.

2.1 *Intraseasonal variability in the tropical Pacific Ocean*

The intraseasonal oscillation (ISO) and semiannual oscillation at 200 hPa in the tropical atmosphere, and their dependence upon the sea surface temperature anomaly (SSTA) of the eastern equatorial Pacific Ocean, are analyzed by means of the estimation of the oscillation kinetic energy and the calculation of the

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correlation between the energy and the SSTA. It is revealed that the positive SSTA corresponds to weaker atmospheric oscillations and the negative SSTA to stronger oscillations (Li and Li, 1999a).

TOPEX/POSEIDON (Ocean Topography Experiment/Poseidon) altimetric data is used to analyze the spatial distribution of ISO in the tropical Pacific Ocean (Liu and Wang, 1999; Hu and Liu, 2002), and the model simulation output from the Parallel Ocean Model (POM) with eddy-resolution is also used for this purpose (Liu and Wang, 1999). As their results show, the quasi 30-day oscillation can be found in the zonal belts about 5°N and 5°S to the east of 160°W. The quasi 90-day oscillation is evident in the zonal belts about 20°N and 20°S, and it is more obvious in the western Pacific Ocean of the 20°N belt. The signal for the quasi 60-day oscillation distributed in the 10°N zonal belt and the 20°S belt is weaker than the quasi 90-day signal although it is distinct in the data. The signal in the 10°N belt is more obvious than in the 10°S belt. In addition, a quasi 60-day oscillation can also be found in the eastern equatorial Pacific Ocean (5°N–5°S, 170°–120°W). It is further reported by Hu and Liu (2002) that the 90-day oscillation with its annual variability is closely related to El Niño/Southern Oscillation (ENSO) occurrence. Besides altimetry data, satellite outgoing longwave radiation (OLR) data (1979–1993) are also used to find the source for ISO in the eastern tropical Indian Ocean and the western tropical Pacific Ocean. The water area where the ISO with a period of 6.5–12.5 pentads is the most vigorous is the eastern tropical Indian Ocean; ISOs with their respective periods can also be evidenced in the tropical Indian Ocean to the northwest of Australia, in the tropical Pacific Ocean to the northeast of Australia, in the south part and the north part of the South China Sea, in the Luzon Strait, and the area to the south of Japan (Wang et al., 2000b).

2.2 *Interannual variabilities of wind, sea temperature, etc. and ENSO process study*

Interannual variability of wind and sea temperature, etc. and the ENSO process of the tropical Pacific Ocean continue to be one of the most interesting subjects in the air-sea interaction studies in China. Long time series of sea surface temperature (SST), precipitation, wind, oceanic heat, geopotential height, and other meteorological or oceanographic observational elements are widely used to determine their interannual variabilities and the ENSO evolution process. The NCEP (National Center for Environmental Prediction)/NCAR (National Center for Atmospheric Research) monthly mean SST and 1000-hPa wind data (1979–1998) are used to study the interannual variability in the tropical Pacific Ocean, Indian Ocean, and Atlantic Ocean, to describe the characteristics related to ENSO events, and to estimate the correlation among the three oceans. It is reported that the contemporary correlation between the regional SSTAs representative for the Indian Ocean and for the eastern equatorial Pacific Ocean is positive and weakly negative between the regional SSTAs for the eastern equatorial Atlantic and for the eastern equatorial Pacific. The positive correlation reaches its greatest value when the regional SSTA for the equatorial Indian Ocean lags 3 months behind the regional SSTA for the eastern equatorial Pacific Ocean, and the negative correlation reaches its maximum when the regional SSTA for the equatorial Atlantic leads the regional SSTA for the equatorial Pacific Ocean by 6 months (Yin and Ni, 2001).

Since the heat content in the tropical Pacific Ocean is an important causative element related to heat exchange between the upper ocean and the above atmosphere, its variability has attracted much attention of Chinese oceanographers. Scientific evidence shows that the heat content in the upper layer above the thermocline of the equatorial Pacific Ocean is accumulated before an El Niño event, and its variability leads the SSTA of the eastern equatorial Pacific Ocean by a few months (Pu et al., 1999a). The location for the maximum lag correlation between the heat anomaly in a water column of the off-equator area and that of the Niño-3 region tends to move anti-clockwise in the northern tropical Pacific Ocean, and clockwise in the southern tropical Pacific Ocean, completing a cycle in about 4 years.

Li et al. (2001b) study the interannual variability of ISO using the daily mean oceanic rainfall data (1979–1991) of the Microwave Sounding Unit and the pentad SST data from the Climate Prediction Center Merged Analysis of Global Precipitation (1982–1992). It is found that ISO is limited to the west of the dateline in a normal year while it can extend further eastward and reach the central-eastern tropical Pacific Ocean in an ENSO year. The most significant correlation between the interannual variability of ISO and SST in the central-eastern Pacific Ocean is located in the Niño-3 region. A numerical simulation result confirms the interannual variability of ISO in the tropical Pacific rainfall by use of the General Circulation Model 3 (GCM3) forced by the observational SST. It is also reported (Wu et al., 2002) that a global Atmosphere General Circulation Model (AGCM) (L9R15 version) forced by SST from the Comprehensive Ocean-Atmosphere Data Set (COADS) is integrated for the period from 1945 to

1993. It is found that there are interannual and interdecadal variabilities in the simulated surface wind over the tropical Pacific Ocean. The model output is compared with the observations, showing a good agreement between the two.

ENSO or ENSO-related studies remain a focus of the air-sea interaction research activities in China, resulting in improvement of the knowledge about ENSO processes and dynamics. Particularly, papers are concentrated in the oceanic subsurface temperature variability and its close relation with ENSO occurrence. Pu et al. (1999b) discuss the evolution of the 1997/1998 ENSO event using the observational data. It is concluded in the case study that the variability of the sea temperature anomaly in the tropical oceanic thermocline and the Kelvin wave propagation play an important and significant role in ENSO evolution, and the subsurface warming, which initially follows the westerly burst, leads the surface warming in the tropical ocean. It is further pointed out (Li and Mu, 1999; and Li, 2002) that the subsurface oceanic temperature anomaly in the equatorial Pacific Ocean is closely related to the occurrence of ENSO. It is the positive (negative) subsurface temperature anomaly that results in El Niño (La Niña) occurrence. The interannual variability of the subsurface temperature in the tropical Pacific Ocean can be attributed to the East Asian monsoon abnormality. SST (1955–1998) in the western tropical Pacific Ocean is analyzed by Chao and Chao (2001), and it is concluded in their study that the positive subsurface temperature anomalies have appeared at a depth of about 120 m depth in the western tropical Pacific Ocean before SST becomes warmer in an ENSO event. Chen et al. (2002), using the XBT (Expendable Bathythermography) data of the upper tropical Pacific Ocean, reveal that the sea temperature anomaly of the north equatorial current (10°N) is closely associated with the subsurface temperature anomaly of the western Pacific warm pool. In the early stages of an ENSO cycle, the warmer water located in the thermocline of the central and eastern Pacific Ocean can be transported westward to the western Pacific warm pool region by the north equatorial current, accumulating in the region, and then extend toward the equator. Therefore the warmer thermocline water transport by the north equatorial current is one of the mechanisms for ENSO occurrence.

Sea surface wind anomalies, which play an important role in the ENSO occurrence and evolution, have also attracted Chinese scientists' attention. It is reported by Zhang and Huang (1998) and Pu et al. (1999b) that the westerly wind anomalies in the western tropical Pacific Ocean initially appear in the western and central Pacific Ocean during an ENSO event, and then are displaced eastward. The SST in the eastern equatorial Pacific Ocean increases after the wind anomaly has become stronger and gradually propagated eastward. The SST reaches its highest value when the wind anomaly becomes located in the central Pacific Ocean. Then SST decreases in the eastern and central Pacific Ocean, and the easterly anomaly appears in the western tropical Pacific Ocean. Finally normal conditions are recovered. In addition to the utilization of the observational data of wind and SST, model simulation is widely used to describe the dynamic effects of the wind anomaly on an ENSO cycle, and to discuss the Kelvin wave reflection and the Rossby wave generation and their effects on the ENSO duration in the Tropics (Zhang and Huang, 1998; Huang et al., 1998b; Yan et al., 2001; Huang et al., 2001). A hindcast for the 1997/1998 ENSO event from an intermediate coupled model and the wind anomaly importance for the ENSO cycle are discussed by Yan and Zhang (2002a). When the model is forced by the observational wind anomaly for the period (1971–2000), it is able to simulate all the ENSO events with a correlation of about 0.63 between the observational Niño-3 SSTA and the model output. The seasonal variability of the westerly anomaly during a composite ENSO event in the western tropical Pacific Ocean is also studied and the similarity of the seasonal variability between the westerly anomaly and the monthly mean divergence is found (Yan and Zhang, 2002b). Based on their model experiments, the characteristics of the seasonal variability can be successfully simulated with a simple equatorial ocean-atmosphere coupled model. It is shown that the model heating terms dependant upon the basic climatic state are necessary in simulating the seasonal variability of the westerly anomaly, playing an important role for forming the westerly anomaly in the western equatorial Pacific Ocean at the beginning of an ENSO event. Then, in the developing or mature phase of an ENSO cycle, SSTA in the eastern equatorial Pacific Ocean is more important for forming the westerly anomaly.

In addition to the zonal wind anomaly, the meridional wind anomaly in the tropical ocean is also analyzed. Zhang et al. (2001a), using the singular value decomposition (SVD) method analyze the meridional wind anomaly in the tropical Pacific Ocean and the Niño-3 index, and indicate that the variability of the meridional wind anomaly leads the SST variability by about 6 months. Zhang and Zhao (2001) utilize an analytic model forced by the equatorial convergence of an ideal meridional wind field, and perform a diagnostic analysis of the model results to determine the effects of Rossby waves excited by the meridional wind anomaly on the SST variability. Zhang et al. (2002a) analyze the SST and the meridional wind of the tropical Pacific Ocean to obtain their periodic variability by means of the Singular Spectrum Analysis (SSA) method. The analysis results show that the variabilities with the quasi four-year period, the quasi two-year period, and the interdecadal timescale are respectively significant. The variability of the quasi four-year period has the greatest variance contribution. They also compare the SSTA patterns which results from the regional meridional winds respectively corresponding to the western tropical Pacific Ocean, the northeast tropical Pacific Ocean, and the southeast tropical Pacific Ocean to find the spatial variability of SSTA and the importance of the regional wind characteristics for the SSTA distribution.

Besides the above ENSO-related studies, some papers discuss the classification and temporal changes of ENSO events. Zhao and Chen (1998), using COADS data and the Southern Oscillation Index (SOI) of the National Climate Center of China, divide both the ENSO events and the La Niña events that occurred since 1956 into two types, namely, the eastern area type and the central area type. They find that La Niña with unusually cold SSTA in the central and eastern tropical Pacific Ocean occurs one year before the ENSO onset of the eastern area type, and ENSO with unusually warm SSTA in the central and eastern tropical Pacific Ocean occurs one year before La Niña onset of the eastern area type. In contrast with the eastern area type, the central and western tropical Pacific SSTA becomes essential for an event of the central area type, with positive SSTA in the central and western Pacific before ENSO of the central area type, and negative SSTA there before La Niña of the central area type.

Zhu et al. (1998) use the objective analysis data from the National Meteorological Center to describe the respective characteristics of the 1976/1977 ENSO event and the 1982/1983 ENSO event and to find the difference in the background of the interdecadal variability in which the ENSO events respectively occurred. The 1976/1977 ENSO occurred in a background where the SST field was relatively cold, the westerly anomaly could be found at the level of 850 hPa over the equatorial Pacific Ocean (0°–80°W), and the SSTA oscillation with a four-year period was being propagated eastward. The 1982/1983 ENSO occurred in a background where the SST field was relatively warm, the easterly anomaly could be found at the level of 850 hPa over the equatorial Pacific Ocean (0°–80°W), and the SSTA oscillation was being propagated westward.

In addition to these observational studies and the numerical model simulations for ENSO occurrence in the tropical Pacific Ocean, analytic models are also used to explain the ENSO-like oscillation between the South China Sea and the western tropical Pacific Ocean (Wang et al., 1999a). The analytic solution of the model coincides with the data analysis. Wang et al. (2000a) further discuss the parameters in the model and propose a method for determining the parameters suitable for the interannual timescale oscillation.

2.3 *Climatic effects of both ENSO and oceanic variability in the tropical Pacific Ocean*

A large number of papers concentrate on the climatic effects of both ENSO and oceanic variability in the tropical Pacific Ocean. It is convenient for reviewing the papers to classify them into 3 categories: oceanic background of the 1998 heavy flood in the Changjiang River basin, ENSO effects on the climate, and others.

2.3.1 *Oceanic background of the 1998 heavy flood in the Changjiang River basin*

The 1998 flood was the heaviest flood of the river basin in the 20th century other than the 1954 flood. It is found that when the flood occurred, the 1997/1998 ENSO event was coming to an end. The background of the air-sea interaction in which the flood was caused, attracted the attention of Chinese scientists. Huang et al. (1998c) analyze the observational data in order to find the climatic and hydrological features and the cause of the catastrophic flood. They find that the flood occurred during the transition of the 1997/1998 ENSO event from its mature phase to its decaying phase, when SST in the tropical Pacific Ocean—especially the subsurface temperature in the western tropical Pacific Ocean—became cooler, and the convective activities around the Philippines weakened, thus the western Pacific subtropical high was situated further southward. As a result of the abnormal climatic situation, abundant moisture which was carried by the Asian summer monsoon from the Bay of Bengal and the South China Sea converged with moisture which was carried from the western tropical Pacific Ocean, initially converging and flowing into the middle and lower reaches of the river and then into the upper and middle reaches, and caused continuous, severe rainfall in the river basin and the catastrophic flood. Guo et al. (2002) using the Global Ocean-Atmosphere-Land System Model of the Institute of Atmospheric Physics/Laboratory of Atmospheric Sciences and Geophysical Dynamics (IAP/LASG GOALS model) forced by global observational SST, reproduce the heavy rainfall over the Changjiang River basin in the summer of 1998 and the subtropical high abnormality over the western Pacific Ocean. A series of numerical experiments are conducted with the observed SST in the selected oceanic regions and the climatic SST in the rest in order to test the regional effects on the rainfall. In addition to the regional effects, two more numerical experiments are also designed with the observed SST in the selected time periods and the climatic SST in the rest in order to test the temporal effects on the rainfall. The results show that SSTA in the Indian Ocean plays a greater role than in the other oceanic areas for the rainfall during the flood, and the SSTA in the Indian Ocean and the western Pacific Ocean are more closely related to the subtropical high abnormalities over the western Pacific Ocean than SSTA in other areas. It is also found that SSTA in the summer of 1998 plays a more important role in the rainfall causing the flood rather than SSTA in either winter 1997 or spring 1998.

2.3.2 *ENSO effects on climate*

Zhang et al. (1999b) study the seasonal precipitation occurring in China when an ENSO process reaches its mature phase respectively in spring, summer, autumn, or winter. They find that positive precipitation anomalies in the composite precipitation patterns are all located in South China no matter whether an ENSO process reaches its mature phase in spring, autumn, or winter, and the anticyclonic anomaly of the lower troposphere is entirely situated to the north of the maritime continent. It is the anticyclonic anomaly that intensifies the western Pacific subtropical high, makes it extend further westward, and results in the positive precipitation anomaly in South China. The composite precipitation pattern in China when an ENSO process reaches its mature phase in summer becomes different from those for the other three seasons. The negative precipitation anomalies in the pattern are located respectively in the furthest southern part and northern part of China, while the positive precipitation anomalies tend to be located in between, i.e., in the lower reaches of the Changjiang River and the Huaihe River Basin. Although the strength of the western Pacific subtropical high becomes intensified, its area is limited to the southeastern periphery of China where the precipitation decreases. Meanwhile the Indian summer monsoon cannot reach the northern part of China providing less moisture inflow. Huang et al. (2000) analyse the observed SSTA and the subsurface temperature data, the NCEP/NCAR reanalysis data, and the data of the daily precipitation in China, and describe their characteristics during the 1997/1998 ENSO cycle and discuss the cycle's impact on the East Asian climate in the summer of 1998. Their analysis shows that the vapor transport by the Asian summer monsoon was very weak in both North China and South Korea in summer 1997 when the strongest ENSO event in the 20th century was rapidly developing, causing the drought and the hot weather in the area; and a large amount of water vapor was continuously transported from the Bay of Bengal, the South China Sea, and the western tropical Pacific Ocean into the Changjiang River basin of China, South Korea, and Japan in winter 1997/1998 when that ENSO event was rapidly decaying. The abnormal situation was associated with the southward displacement of the western Pacific subtropical high, resulting in the severe floods in those regions.

Chen et al. (2000) analyze the frequency of cyclone occurrence in the Southern Hemisphere (0°–80°S, 70°–170°E) and its respective correlations with the SST in the eastern equatorial Pacific Ocean and with the southern oscillation index. They find that the correlations depend on the latitudinal zones where the cyclones occur and the correlation coefficient between SST and cyclone frequency reaches its maximum when SST lags 24 months behind the frequency of the cyclone occurrence.

2.3.3 *Variabilities in the western Pacific warm pool and its climatic effects*

Weng et al. (1998) study not only the variability of the subtropical high but also the variability of the area of the western tropical Pacific warm pool. The time series of both are analyzed showing the same spectral peak at a period of 46.7 months. The subtropical high becomes stronger (weaker) when the warm pool area is larger (smaller). Zhang et al. (1999a) identify the two climatic precipitation regions of North China by use of the comparative analysis method, and find that one of the two regions is closely related to the heat content of the western tropical Pacific warm pool, with the best negative correlation between the wet season precipitation in this region and the warm pool heat content in October of the previous year. The wet season precipitation of another region is closely related to the heat transport of Kuroshio in winter of the same year.

Li et al. (1999a) study the seasonal and interannual variabilities of oceanic temperature in the western Pacific warm pool and their impacts on climate including the influence on the East Asian monsoon, the teleconnection with the atmospheric circulation, and the effect on ENSO occurrence. They find that the subsurface temperature in the western Pacific warm pool is more closely related to the SST in the eastern equatorial Pacific Ocean rather than the local SST, the positive (negative) SSTA in the warm pool is related to the stronger (weaker) summer monsoon with the EPA wave-train pattern stretching further (less) northward to higher (lower) latitudes, and the occurrence of ENSO is closely related to the subsurface temperature anomaly in the warm pool and the quick development of ENSO to the quick eastward propagation of the subsurface temperature anomaly.

Zhao et al. (2000b) study the long term variabilities in the western tropical Pacific warm pool, and find that its temperature decreases in the first decade of the 20th century and increases (by about 0.5°C) in the 1970s. When the warm pool temperature increases, the subtropical high extends further westward in the northwest Pacific Ocean and its ridge is displaced further southward, resulting in a change of the precipitation pattern in China, i. e. less rainfall in the north and more rainfall in the south. They also find that El Niño events become more frequent and stronger in the warm period and La Niña events become more frequent and stronger in the cold period.

Liu and Wang (2000) analyse the seasonal variation of SST around the Indonesian Archipelago. They find that the maximum longitudinal SST difference between the north and the south is located at 110°E in boreal winter while it is both in 130°–145°E and at 110°E in boreal summer. The seasonal variation is advantageous to the formation and maintenance of the cross equator air-flow toward the north at 0°, 105°E.

2.3.4 *Varabilities of SST in the tropical oceans and the subtropical high over the northwest Pacific Ocean and their climatic effects*

Li and Li (1999b) analyze the air temperature variability of Sichuan Province and SST variability in the western tropical Pacific Ocean. They find that both factors have the same tendency within the 50 years from the warmest decade (1950s) to the coldest decade (1980s) of the 20th century, with a relatively abrupt change occuring in the 1970s. When SST in the western tropical Pacific Ocean increases (decreases), the subtropical high over the western Pacific Ocean extends further westward (eastward) and the air temperature of the Sichuan Province becomes warmer (cooler). Ying and Sun (2000) analyze the observational data to study the response of the subtropical high over the northwest Pacific Ocean to the SST of the tropical oceans. They find that the strength of the subtropical high is closely related to SSTA of the central and eastern equatorial Pacific Ocean, the Indian Ocean, and the western Atlantic Ocean. The subtropical high becomes stronger for the SST pattern of the El Niño type, and weaker for the SST pattern of the La Niña type. Zhao and Wu (2002) use wavelet analysis and the Expirical Orthogonal Function (EOF) method to analyze the SSTA variability of the tropical Pacific Ocean. They also analyse the variabilities of the subtropical high index and precipitation of the Changjiang River basin and of North China. They conclude that the variabilities with a 60-year period play an important role in the abundance of the rainfall in the river basin and the droughts of North China in recent years.

3. Monsoon-related air-sea interaction

Both the South China Sea monsoon and the East Asian monsoon are important climatic systems with annual cycles, which influence the precipitation and the agricultural economics in China. As the monsoon cycle is affected by the thermal condition of the upper oceans adjacent to China, the monsoon-related air-sea interaction is one of the most important subjects in oceanography and meteorology in China.

3.1 *East Asian monsoon*

A numerical diagnostic study on the effects of the duration of the positive SSTA in the eastern equatorial Pacific Ocean in winter and spring on the East Asian summer climate is conducted by Long and Li (1999a). Their simulation results from the IAP 2-layer AGCM and 9-layer spectrum AGCM show that the atmospheric response and climate abnormality in East Asian affected respectively by the positive SSTA durations (January only, January–February, January–April) are quite similar to each other. It is found that the strength of positive SSTA might play a more important role in the summer climate than the positive SSTA duration. Therefore greater attention should be paid to the stronger positive SSTA even if its duration might be shorter. Peng et al. (2000) propose a new definition for an East Asian monsoon index which can better reflect the annual and interannual variations of the subtropical high over the northwest Pacific Ocean, and discuss the correlation among the SSTA in the eastern equatorial Pacific Ocean, the subtropical high in summer, and the East Asia summer monsoon. Their results show that the East Asian summer monsoon becomes weaker and the subtropical high is stronger and extends further southward and westward in summer if SSTA increases in the eastern equatorial Pacific Ocean in the spring of the same year. Following the SSTA increases in spring, the rainfall increases in the Changjiang River basin in summer and decreases in South China, the Hetao area, and the area to the east of Hetao. The reverse is also remarkable if the SSTA decreases in spring. Yu et al. (2001) use the monthly precipitation data (1951–1998) of the 115 stations of East China and the global SST data of COADS to calculate the lag correlation coefficient between the regional precipitation and the regional SST, and to study the predominant oceanic region in the forcing of the East China summer monsoon rainfall. They find that the seasonal variations of rainfall at any one of the four sub-regions are similar to each other in East China, with a monsoon rainfall peak in June or July. They work out the respective lag correlation coefficients between summer monsoon rainfall in the Changjiang River basin and the mean SST in each of the seven sub-regions in the Pacific Ocean and the Indian Ocean with SST leading the rainfall, and obtain the regression equation of the summer monsoon rainfall for the basin, which depends upon mean SST at each oceanic sub-region with respective leading times. The hindcast results for the summer monsoon rainfall by use of the regression equation are consistent with the observed rainfall. Li and He (2001) study the interdecadal features of the East Asian monsoon and the monsoon rainfall over North China, and their relations with the North Pacific SSTA by use of the NCEP/NCAR reanalysis data ($2.5° \times 2.5°$), SST data, and rainfall data of National Climate Center of China. They find that the East Asian summer monsoon was stronger before 1926 together with the abundance of rainfall in North China. And it became weaker after 1976 together with the rainfall deficiency in North China. They also find that the correlation between the rainfall of North China and the SSTA in the North Pacific Ocean was much better before 1976.

3.2 *Interaction between Asian Monsoon and ENSO*

A large number of papers concentrate on the interaction between Asian monsoon circulation and ENSO. Huang et al. (1998a) find that the longitudinal vapor transport by the East Asian monsoon is much greater than the latitudinal, and that the water vapor convergence which causes the monsoon rainfall depends upon both the monsoon circulation pattern and the water vapor advection path. Jin and Tao (1999) further study the rainfall in East China and find that it is closely related to the ENSO cycle.

Regarding the monsoon circulation pattern and its relation to ENSO, Tao and Zhang (1998) analyze the geopotential height fields and atmospheric circulation patterns respectively for El Niño and La Niña, indicating that a certain circulation pattern corresponds to the weakening of the winter monsoon in East Asian in an ENSO year. To explain the abnormality of Asian monsoon circulation in an ENSO cycle, Ren and Huang (1999) attribute it to the abnormal convection pattern forced by the SSTA distribution related to ENSO in the tropical Pacific Ocean, i.e., the thermal convection strengthening in the middle and eastern equatorial Pacific Ocean and the weakening in the western equatorial Pacific Ocean result in a dipole of the convective activity or the thermal source over the tropical Pacific Ocean which is favorable for strengthening anticyclonic circulation over the South China Sea and southwest monsoon air-flow over the Changjiang River basin and the Huaihe River basin. Ni and Sun (2000) find that heavy drought or flood disasters often occur in China in the developing or decaying phase of ENSO. Huang (2001) uses rainfall data (1951–1999) of China to analyze the association of drought or flood with various phases of an ENSO cycle. He indicates that the summer monsoon rainfall tends to be abundant in the Changjiang River and Huaihe River basins of China, Japan, and Korea if it coincides with the developing phase of an ENSO cycle, and it tends to be deficient in North China and South China. The reverse summer rainfall distribution can be found in the ENSO decaying phase. Wang et al. (2001) further indicate that the ENSO effect on the East Asian summer monsoon circulation lags behind the ENSO evolution, i.e., the anti-cyclonic circulation becomes strengthened in Northeast Asian, and the subtropical high extends further westward in summer after an ENSO event has reached its mature phase. As the Asian summer monsoon usually brings a large amount of water vapor into India, South Asian, and East Asian and as it influences the vapor transport to the same areas, the ENSO effects on the summer monsoon circulation play an important role in the regional vapor transport.

In addition to studies of vapor transport and its sources related to the summer monsoon and ENSO, the relation between the winter monsoon and ENSO is also studied. Mu and Li (1999) study the coincidence of ENSO occurrence with the strengthening of the winter monsoon in East Asian by means of observational data (1950–1989) analysis. They find that the winter monsoon becomes stronger (weaker) in East Asia before an El Niño (La Niña) event occurs. They indicate that ENSO signals are better reflected and included in the interannual anomaly of the winter monsoon in East Asia. Long and Li (1999b), using an AGCM heated by the typical SSTA of the eastern Pacific Ocean during ENSO, study the effect of a typical ENSO event on the subsequent monsoon activity in East Asia. They find that in the summer after an ENSO event has occurred, the subtropical high becomes stronger. Its ridge tends to be displaced northward and its area extends further westward causing rainfall deficiency in East China and North China. In winter after La Niña has occurred, a rainfall deficiency happens in the Changjiang River and Huaihe River basins, causing a different rainfall distribution. Zou et al. (2002) further confirm that the Asia winter monsoon moving southward can excite the strong convective activities in the western tropical Pacific Ocean and influence the ENSO cycle. They point out that the influence is reflected in the quasi-biennial oscillation mode. Therefore the Asia winter monsoon plays an important role in ENSO occurrence. And consequently, ENSO will influence the East Asia monsoon.

A review of the studies on the interaction between the ENSO cycle and the Asia monsoon is given by Huang and Chen (2002) and more details on the recent progress in this area can be found there.

3.3 *South China Sea monsoon*

Zhao et al. (2000a) analyze the SSTA field in May for the South China Sea and the eastern tropical Pacific Ocean by means of the EOF method to study the South China Sea monsoon onset and its association with the SSTA field. They find that the positive maximum value of the first characteristic vector is centered at Sumatra of Indonesia showing its close relation with the monsoon onset. Furthermore, the South China Sea monsoon starts earlier (later) when the SST becomes warmer (cooler) than usual in the sea area around Sumatra. Zhao and Chen (2000b) also analyse the seasonal and the interannual variations of the South China Sea warm pool (with sea temperature greater than 28°C) and discuss their relation with the South China Sea monsoon onset. The results show that the warm pool has an obvious seasonal variation with its largest area found in May to June and its smallest area in December to February. The rapid transitional months are respectively March–April and October–November, leading to the monsoon seasonal reverse. The monsoon onset can be closely related to the warm pool interannual variability. The summer monsoon starts later (earlier) than usual if the warm pool becomes warmer (cooler) in the previous winter and spring. The subsurface variability of the tropical Pacific-Indian Ocean and its correlation with the strength of the South China Sea monsoon are analysed by Zhang et al. (2001b, 2002b). Zhang (2001b) find that the thermocline depths of the central equatorial Pacific Ocean and Bay of Bengal are positively and closely correlated with the strength of the monsoon and can be used as a predictor in monsoon prediction. Zhang et al. (2002b) also find that the sea temperature at a 120-m depth is the best correlated with the monsoon strength. They classify all the South China Sea monsoon cases (1995–1998) into four kinds , discuss the subsurface sea temperature field at a 120-m depth and the wind field at 850 hPa respectively for the four kinds by means of the composite analysis method, and explain their scientific significance for the monsoon and ENSO prediction.

4. Decadal-interdecadal variability in the Pacific Ocean

Oceanic data are analysed for surface air temperature, the subtropical high activities over the northwestern Pacific, and the SSTA in the equatorial Pacific. It is shown from the data analysis that there are clear quasi-decadal oscillation signals (Li, 1998). It is also found that the climate variations in East Asia, such as the surface air temperature, the precipitation, and the onset date of Meiyu in the Changjiang River basin, have a quasi-decadal oscillation similar to that mentioned above. It is deduced that it is the quasi-decadal oscillations of the whole air-sea system that influence those climate variations and oceanic variations.

Signals of the interdecadal variability in the Pacific Ocean are examined by use of the Complex Expirical Orthogonal Function (CEOF) method and composite analysis method for XBT temperature data obtained in the period from 1950 to 1993 (Wang and Liu, 2000). Such signals are propagated southwestward from the central North Pacific and subducted to the subtropical region. It is found that the thermal anomalies subducted from the central North Pacific to the east of the dateline can only reach 18°N in the western tropical ocean. There has been no further southward propagation than 18°N due to a certain barrier. However the origin of the interdecadal oceanic signal in the western tropical Pacific can be traced to the southern tropical Pacific. These variabilities reflect the nature of the thermocline circulation. Yang et al. (2002) analyse the data (1950–1998) from the Maryland Ocean Data Assimilation and the NCEP/NCAR atmospheric reanalysis data to study spatio-temporal structures of interannual and interdecadal variations in the global ocean-atmosphere system. They conclude that the oceanic interannual variations are dominant in the tropical Pacific while the oceanic interdecadal variations are mainly confined to the mid-to-high latitudes, the off-equator Pacific, and Atlantic. On the other hand, the atmospheric interannual and interdecadal variations both appear in the mid-to-high latitudes especially over the polar regions, with less coherence between the interannual air temperature variation and the interannual sea level pressure variation but better coherence between the interdecadal variations. The interannual variation of the mid-to-high latitude atmosphere seems to be an intrinsic variation, which cannot be related to the interannal variation of the tropical upper ocean with ENSO features. They also find that an abrupt change in the global air-sea system happened in the 1970s, such as the air temperature increase in a large area of the world, especially in Siberia and the polar regions, the SST increase in the eastern tropical Pacific Ocean and the western coastal waters of North America, South America, and Africa, the air-temperature decrease in North Tibet and Greenland, and the SST decrease in mid latitude waters of the North Pacific Ocean and high latitude waters of the Southern Hemisphere.

Zhu et al. (2002) analyze the data (1951–1995) of the 500-hPa geopotential height and monthly mean SST by means of the Singular Value Decomposition (SVD) method to study the coupled pattern of the mid and low latitude atmosphere/ocean interaction and its decadal variation. They find that the PNA (Pacific and North American) teleconnection pattern is closely related to El Niño, and the Pacific–Japan (PJ) teleconnection pattern to La Niña. They also find that the abrupt changes of the coupled system happened in the middle 1970s, with the significant SST increase in the central and eastern tropical Pacific Ocean and the decrease in the middle part of the North Pacific Ocean. The PNA pattern in winter becomes strengthened after the middle 1970s and no PJ pattern appears before the middle 1970s.

More details of the interdecadal variability of the air-sea interaction system in the Pacific region can be found in Li et al. (2001a).

5. Air-sea interaction in the North Pacific Ocean

Zhang et al. (1998) analyse the sea surface turbulent heat flux anomalies (including sensible and latent) and their effects on SSTA in the North Pacific Ocean in wintertime using the data extracted from a long-term integration of a coupled ocean-atmosphere general circulation model. The relative importance of the sea surface heat flux components for determining the SSTA variability has been studied and compared with the other oceanic dynamic processes. They find that the turbulent heat fluxes play a major role in the SST variability in most of the extratropical North Pacific Ocean except in a central patch of the basin where the effect of the oceanic horizontal advection on SST is not negligible. The latent and sensible heat flux anomalies in the model are closely related to the SST tendency rather than SSTA in the extratropical Pacific Ocean during wintertime. Their results coincide with the analysis results by Cayan from COADS and by Reynolds et al. from the NCEP data. The model runs support that the atmospheric role on the ocean is dominant in the air-sea interaction over the extratropical ocean in wintertime rather than the oceanic forcing on the above atmosphere, while the ocean plays a dominant role in the Tropics. The first EOF mode of the SST tendency from the model output and its correlations with the sea level pressure are similar to the results by Wallace et al. from the observational data. Therefore, it is the anomalous large-scale atmospheric circulation that affects SSTA in most of the extratropical Pacific Ocean especially in the western Pacific through the sea surface turbulence heat fluxes. Jiang (1998) studies the heat transfer between air and sea in the mid-latitude North Pacific Ocean. He finds that the heat transfer from sea to air has obvious seasonal features becoming the greatest in December and the least in June. The spatial distribution of the heat transfer is closely related to the distribution of oceanic currents. It is greater in the warm current area and less in the cold current area. The seasonal variations of the heat transfer between air and sea are more obvious near the west boundary where Kuroshio or Oyashio flows than near the east boundary where the Alaska current or California current flows. The meridional gradient of the heat transfer becomes the greatest in 37.5°–43.5°N, west of 160°E in March and almost vanishes in June. The sea surface heat budget also has a seasonal variation with the net heat from sea to air in December in any area of the North Pacific Ocean and the net heat from air to sea in June in any area of the ocean. The heat budget ratio, which depends upon the latitude of the sea area, has a different tendency in December from the tendency in June.

In addition to the extratropical water heat budget studies, Xie and Liu (2001) detect a wind wake trailing westward behind the Hawaiian Islands for 3000 km, many times longer than observed anywhere else. The wind wake drives an eastward oceanic current and draws warm water 8000 km away from the Asian coast, leaving remarkable changes in surface and sub-surface temperature. Located in the steady trade wind zone, Hawaii triggers a kind of air-sea interaction, which provides the feedback to sustain the influence of these small islands over a long stretch of the North Pacific.

6. Air-sea interactions in the Indian Ocean

Air-sea interaction in the Indian Ocean has been focused on much more than before by Chinese scientists. Interdecadal variability in the tropical Indian Ocean is analysed (Wang et al., 1999b), based on the long-term climatic observational data. It is shown in the study that the strong interannual signals formed at the sea surface can reach the seasonal thermocline depth, where the sea temperature anomalies will keep a longer time memory with an interdecadal feature. The longer time memory in the thermocline can be imitated by means of a damping process with exponential decay in time from the peak phase of the selected strong interannual events. Therefore a possible dynamic explanation for the interdecadal variability in the tropical Indian Ocean is proposed as follows. The irregular interannual signals can lead to a slowly evolving climatic background with the interdecadal timescale feature through the damping processes in the seasonal thermocline.

Xiao et al. (2000) use the IAP-GCM9L (Institute of Atmospheric Physics-General Circulation Model with 9 layers) model to simulate the atmospheric response to the SSTA pattern during an ENSO occurrence phase with warm SST in the western Indian Ocean and cool SST in the eastern Indian Ocean, and to study the effects of the SSTA pattern on Asian climate. It is already known from published literature that the equatorial Pacific SSTA pattern during ENSO brings about the global climatic abnormality. If the SSTA pattern of the Indian Ocean is taken into account, the climate abnormality will become enhanced in the Bay of Bengal, Indo-China Peninsula, Indonesia, India, and China. The main abnormality in climate is that the Indio-China Peninsula becomes much drier, and rainfall decreases in North China and increases in a zone along the Changjiang River from Southwest China to Southeast China.

Zhou et al. (2001) analyze SST of the Indian Ocean, based on the Global Sea-Ice and Sea Surface Temperature Dataset (GISST) from the British Hadley Climate Centre, to study the SST variability of the Indian Ocean during the 20th century by means of various statistical methods. Their main conclusions are as follows: SST of the northern Indian Ocean and the western equatorial Indian Ocean has obvious monsoon features with its coldest values during the mature phase of the southwest monsoon season, while SST of the southern Indian Ocean has a relatively regular annual cycle except that it lags about 2 months behind the solar radiation cycle. Seasonal variability is not obvious in the central and eastern equatorial Indian Ocean. SST of the tropical Indian Ocean north of 20°S has not only a warming trend in the last 50 years, but also a positive correlation with the eastern equatorial Pacific Ocean. The correlation coefficient between the equatorial Indian Ocean SST and the Niño-3 index becomes the greatest when the former lags 4 or 5 months behind the latter. Positive correlation can also be found among the SSTA of the southern Indian Ocean, SSTA of the equatorial Indian Ocean, and SSTA of the western Pacific warm pool. SSTA of the southern Indian Ocean with greater fluctuation than SSTA of the equatorial Indian Ocean is better correlated with SSTA of the western Pacific warm pool, as their time series show (after the harmonic waves shorter than a 10-a period has been filtered).

Wu et al. (2000) use thermal adaption theory to study the impact of SSTA in the Indian Ocean on the weather of South China and the subtropical high over the western Pacific Ocean. It is shown that in the first stage of the atmospheric thermal adaption to the SSTA in the ocean, the in situ anomalous cyclonic circulation of the lower troposphere and the deep convective precipitation to its east due to the strengthening of the southerlies will be generated, and in the second stage of the adaption to the latent heating from the condensation of the precipitation, the anomalous anticyclonic circulation will be produced at 500 hPa over the western Pacific Ocean and at 200 hPa over South Asia. Therefore their conclusion is that both stages of the atmospheric thermal adaption to the SSTA in the Indian Ocean are important mechanisms for the abnormality of the subtropical high with the corresponding climate variability over the East Asian monsoon region. Li and Mu (2001a, b) study the SST variation with its dipole oscillation feature in the equatorial Indian Ocean by use of observational data as long as about 100 years. The dipole oscillation feature with higher SST in the west of the ocean and lower SST in the east during its positive phase and with higher SST in the east and lower SST in the west during its negative phase becomes more obvious in September–November and less obvious in January–April. Generally speaking, the amplitude of the positive phase is greater than the negative. The interannual variation of the dipole has a 4–5-year periodicity and the interdecadal variation has a 25–30-year periodicity. Significant impact of the dipole on the Asian monsoon activity can be found because the wind field in the lower troposphere over South Asia, the Tibetan high in the upper troposphere, and the subtropical high over the northwest Pacific Ocean are all related to the dipole. There is also some scientific evidence for the dipole effects on the atmospheric circulation in North America and the southern Indian Ocean region (including Australia and South Africa).

Zhou and Zhang (2002) study the air-sea heat flux exchange of the Indian Ocean by use of the COADS data. They find that SSTA is closely related to the net sea surface heat flux in the tropical Indian Ocean, especially in the wintertime in the central-eastern Indian Ocean and in the summertime in the western and northern Indian Ocean. However, the evolution of SSTA has less correlation with the net sea surface heat flux in the other areas of the ocean, where SSTA evolution might be dominated by the oceanic dynamical processes. The normalized covariance analysis shows that the latent heat prevails over the sensible heat, shortwave radiation, or longwave radiation in forcing the atmosphere in the tropical Indian Ocean. Although the sensible heat flux is less in quantity than the latent in 20°N–20°S, its zonal mean is more significantly correlated to SST than the latent heat flux.

Yu et al. (2002) replaced the oceanic model of the NCAR Climate System Model version 1 (CSM-1) with IAP L30T63 GOCM (General Ocean Circulation Model-Version L30T63), and they modified other components of CSM-1 to set up a Flexible Coupled GCM version 0 (FGCM-0). FGCM-0 has been run for a 60-year integration without any flux correction and it can produce not only a reasonable climatology but also some interannual features such as an ENSO-like event in the tropical Pacific Ocean, dipole pattern in the tropical Indian Ocean, and others. After comparing FGCM-0 with CSM-1, common inadequacies can be found, for example, overestimation of the sea ice in the north Pacific Ocean, false double ITCZ, and others. The inadequacies might be attributed to errors into the atmospheric model as the model output is analyzed.

7. Air-sea interaction in global oceans

Studies of air-sea interaction in the global oceans by Chinese scientists mainly concentrate on the regional features and their comparison among the regions, diagnostic studies for the Indian-Pacific interaction system by use of the observational data and/or model output, and other aspects.

Wu and Wang (1998) analyze the data (1949–1989) of the summertime 500-hPa geopotential height field over the mid-latitudes and SSTA in the northern Pacific Ocean and the northern Atlantic Ocean by use of the rotated principle component method and the cross correlation technique. The analysis results show that the major spatial patterns of the summertime 500-hPa geopotential height anomaly can be divided into the subtropical (ST), the polar and American (PA), the four wave (FW), and the three wave (TW) patterns, while the major patterns of the summertime SST in the North Pacific Ocean are the eastern equatorial Pacific (EEP), the Bay of Alaska (BAL), the central tropical Pacific (CTP), and the northern North Pacific (NNP) patterns, and those of SST in the North Atlantic Ocean are the equatorial Atlantic (EAL), the Caribbean Sea (CAR), the eastern North Atlantic (ENA), and the central North Atlantic (CNA) patterns. The summertime correlation is not so close as the wintertime one between the geopotential height anomalies and the SST anomalies, and it is especially insignificant between the equatorial SSTA and the 500-hPa geopotential height of the mid-latitudes. The best correlations between SST and the 500-hPa height are spatially stationary to some degree in the North Pacific Ocean, and they seem to be well organized with wave chain patterns.

Wu and Meng (1998) use the observational data to study the seasonal variation of the Indian Ocean SST, and estimate the correlation between SSTA of the equatorial Indian Ocean and SSTA of the eastern equatorial Pacific Ocean. Significant positive correlation between the two can be found, which is associated with the strong coupling between the monsoon zonal circulation over the equatorial Indian Ocean and the Walker circulation over the Pacific Ocean. The two circulation cells work together much like a pair of gears operating over the tropical Indian and Pacific Oceans (denoted as GIP). Their results show that ENSO events are closely linked with the GIP operation. A cold (warm) event corresponds to a "positive (negative)" rotation of GIP. The surface airflow of the two cells converges to form the upper branch of the cells, near the Indonesia archipelago where the "gearing point" is located. The analysis of ENSO events after 1980 shows that the appearance first of the "gearing point" , which appears first over the Indonesia, over the Indian side before an ENSO event will propagate gradually eastward during the event evolution phase and the associated anomalies of SST and u-component of the 850-hPa wind to the east of the gearing point will move eastward approaching the dateline. Finally, the ENSO event occurs in the eastern equatorial Pacific Ocean. They conclude that the anomaly in the monsoon zonal airflow over the Indian Ocean can affect the air-sea interaction over the eastern Pacific Ocean in virtue of GIP and trigger the warm event. Beside the observational data analysis, Meng and Wu (2000) analyze the model output from the IAP/LASG GOALS model and find that GIP is well represented in the model. The results from the sensitivity experiments for the regional anomalous zonal winds reveal that through the GIP gearing, the atmospheric anomaly in either the equatorial Indian Ocean or the equatorial Pacific Ocean will cause the SST anomaly in the other. Therefore GIP is considered to be the atmospheric bridge linking ENSO events in the Pacific Ocean on the one end and zonal wind of the Asia monsoon over the Indian Ocean on the other. Zhou et al. (2000) use the IAP/LASG/GOALS model to study the relationship between the thermohaline circulation (THC) and climate variability. They find that the strength of the North Atlantic THC is negatively correlated with the North Atlantic Oscillation (NAO). Based on this negative correlation and the instrument-based climatic data such as air pressure and SST, they estimate the THC variability of the 20th century with the strengthening periods in 1867–1903 and 1934–1972 and the weakening periods in 1904–1933 and 1973–1994.

Li et al. (1999b) analyze monthly mean SSTA (from COADS) and 500-hPa height (H_{500}) field (from the National Meteorological Centre of China) by means of the CEOF method to study the low-frequency variabilities of SSTA in the global tropical waters and H_{500} field in the Northern Hemisphere. Both quasi-biennial and 3–7-year oscillations with phase-lock characteristics can be found in the SSTA and H_{500} field. The H_{500} variability lags about 2 months behind the SSTA. The component for the 3–7-year oscillation of H_{500} has a stationary wave pattern like the PNA pattern, while the component for the quasi-biennial oscillation of H_{500} has a progressive wave feature.

Ma et al. (2001) analyse the monthly mean wind data at 1000 hPa from NCEP/NCAR and the SST from COADS by use of the SVD method and compare the regional difference of the main parameters and the first singular vectors respectively for the western, the central, and the eastern tropical Pacific Oceans, the Atlantic Ocean, and the Indian Ocean. The results show that the global tropical oceans can be divided into three kinds depending upon how the air-sea interaction works. ENSO is the main process for the air-sea interaction in the central and eastern Pacific Ocean, both the ENSO process and the longer timescale process play an important role in the air-sea interaction in the Indian Ocean, and more than two processes work together for the air-sea interaction in the Atlantic Ocean so that the ENSO cycling becomes less obvious.

Zhang and Qian (2001) comprehensively analyse the monthly mean data of the surface wind, surface air temperature, SST, humidity, and sensible and latent heat flux by use of the lag correlation method to determine the seven key regions for the global air-sea interaction. It is shown from the analysis results that SST is closely related to the air temperature in all of the regions, especially in the central and eastern Pacific Ocean, and the southern Indian Ocean, SST is better correlated to surface wind in the central and western Pacific Ocean than in the others, and SST is better correlated to the sensible and latent heats in the eastern Pacific Ocean, the western Pacific Ocean, the Northwest Pacific Ocean, and the southern Indian Ocean than in the others. Therefore those better-correlated meteorological elements can be used for the regional SST forecasting.

Yin et al. (2001) comprehensively analyze the monthly mean data (1979–1998) of SST, Outgoing Longwave Radiation (OLR), and the 1000-hPa zonal wind from NCEP/NCAR reanalysis data. The interdecadal difference of the Indian Ocean dipole can be found with the dipole features less obvious in the 1980s and more obvious in the 1990s. It is suggested that there is interaction between the tropical Indian Ocean and the tropical Pacific Ocean, and the intensification of the Pacific ENSO in the 1990s can be attributed to the influence of the strengthening of the Indian Ocean dipole.

In addition to the studies of air-sea interaction in the tropical and mid-latitude oceans, some studies concentrate on the teleconnection between the polar region and the other areas. For example, Chen and Qin (2000) analyze the monthly mean SST data of the tropical Indo-Pacific Ocean from COADS to study the SST variability in the Tropics and its relation with the Antarctic sea-ice extent, especially with the Ross Sea ice. They find that the most significant correlation appears when the tropical SST lags 16 months behind the Antarctic sea ice. Wu et al. (1999) analyze the data (1954–1989) of the sea ice in the Polar regions and the rainfall in North China, and calculate the correlation between the two. They find that the sea ice extent in winter in the Kara Sea and the Barents Sea is negatively correlated with the rainfall of the Haihe and Liaohe River basins in the following August and the sea ice extent in Baffin Bay and the Davis Strait in winter to the rainfall of the mid-upstream of the Yellow River in the following July, with the best correlation being about –0.6585. Wu et al. (2001) also use the IAP 2-level GCM to study the influence of the variability of both the Arctic sea-ice thickness and extent on the atmospheric circulation over East Asia. Their model results indicate that a more reasonable description of the sea ice thickness will improve the simulated patterns for the Siberian high and Icelandic low in winter, and will intensify both the summer monsoon and the winter monsoon over East Asia. Furthermore, the spatial variability of the sea ice thickness can excite the teleconnection wave trains over the Eurasian continent and the planetary wave propagation from the western Pacific to the eastern Pacific in the lower latitudes. Control run experiments also show that a larger (smaller) sea ice extent in the Barents Sea in winter will result in the positive (negative) Sea Level Pressure (SLP) anomaly over the central North Pacific, Aleutian low weakening (deepening), the light (heavy) sea ice condition in Bering Sea in the following spring, the deepening (weakening) of the thermal depression over Asia, and the further northward (southward) displacement and the strengthening (weakening) of the subtropical high over the western Pacific Ocean in the following summer.

Fu (1999) studies the general features of occurrence frequency, spatial distribution of locations, lifecycle, and cloud patterns of polar lows over the Japan Sea and the adjacent Northwest Pacific Ocean in the 1995/1996 winter by means of the data analysis from field observation and satellite remote sensing. It is shown that polar lows develop the most frequently in mid-winter over 35°–45°N in the Japan Sea and 30°–50°N in the Pacific and rarely form over the Eurasian Continent. Their life-cycle is usually 2–3 days over the Pacific Ocean and 1–2 days over the Japan Sea because of the narrow width of the Japan Sea and influence of the Japan Islands on their decaying. Generally speaking, polar lows over the Japan Sea have tight spiral cloud patterns in the satellite images with a clear "eye" at the mature stage. The greater air-sea temperature difference in the Japan Sea affected by the Tsushima current in winter provides the favorable heating conditions for their formation.

8. The field experiments and cruise surveys

The South China Sea Monsoon Experiment (SCSMEX) is an international cooperative project in which China plays a major role in studying the air-sea interaction processes related to the South China Sea monsoon. Three research vessels, *Xiangyanghong 14*, *Science 1*, and *Experiment 3* have been involved in the field experiment of the project for two months in 1998. Measurements of physical oceanography, meteorology, and marine chemistry were conducted, including Conductivity-Temperature-Depth (CTD) casts, Acoustic Doppler Current Profiling (ADCP), sea surface meteorological observations, high altitude soundings, and marine chemistry water samplings. The multi-ship and multi-discipline observations lay the foundation of the basic research for understanding the processes of the monsoon transition and its northward progression in the South China Sea in late spring and early summer, and the oceanic response to the monsoon atmospheric circulation. The research vessels for the field experiment of SCSMEX are supported by the Chinese Academy of Sciences and the State Oceanic Administration of China.

In addition to SCSMEX field observations, a program called the "Pacific-Indian Warm Pool, Its Current System and Air-sea Interaction", is funded by Chinese Ministry of Science and Technology and the National Natural Science Foundation. A pilot study of this program started in 2001–2002. Three Argo-floats have been deployed in the warm pool region on board R/V *Snow Dragon* when the ship navigated toward Antarctica, and some XBT probes were deployed in the Tropics as well. The program will help the further understanding of the ENSO dynamics and the variability in the tropical waters.

The Southern Ocean near Prydz Bay is another sea area where Chinese scientists frequently conduct air-sea field experiments on board the Chinese R/V *Snow-Dragon*. The program, "Physical Process Study of Air-sea-ice Interaction in the Antarctic Ocean (1996–2000)", supported by the State Oceanic Administration of China, and five summer cruises of the southern ocean expeditions were completed in the five years, obtaining full depth CTD data and water samples for chemistry analysis.

9. Conclusion

A large number of papers have been published and great efforts made in the four-year period by the Chinese oceanographic and meteorological community in the air-sea interaction studies. Although great progress has been made in almost all aspects of this research field in China, there are still some important problems or deficiencies left for future study and improvement, especially in field observation and forecasting practice by use of the air-sea interaction theory. Yet it is too difficult to summarize all the activities of this field in a short report like this, although the authors wish that this difficulty could have been better managed in organizing this report.

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