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論　文　目　次

論 文 内 容 要 旨

A 'regime shift' is characterized by an abrupt transition from one quasi-steady climatic state to another, and its transition period is much shorter than the lengths of the individual epochs of each climatic state. In the present study, the years when regime shifts occurred in the global ocean are detected using the sea surface temperature (SST) field instead of some indices, and changes at the regime shifts in the SST and the atmospheric circulation fields are described. Furthermore, relations between regime shifts and dominant variation modes or tropical variation are investigated.

In Chapter 1, a role of SST in the climate system and interannual to interdecadal variations in the SST field are surveyed, and previous studies of regime shifts are reviewed. Then, scope of the present thesis is described.

In Chapter 2, analyses are performed in the winter Northern Hemisphere SST field, where the regime shifts have been already pointed out by many studies. Before the detection of regime shifts, in order to detect organized patterns of the SST variations, an empirical orthogonal function (EOF) analysis is adopted. As a result, it is found that the first mode is identical to El Nino/Southern Oscillation (ENSO) and so-called Pacific Decadal Oscillation (PDO), and corresponds to the Pacific/North American (PNA) pattern. The second mode, which relates to the Arctic Oscillation (AO), has a zonally elongated signal in both the North Atlantic and the North Pacific. EOF analyses to each oceanic basin are made separately and the robustness of these modes is confirmed.

In this chapter, the regime shifts are defined as the 'significant' and 'systematic' changes between the two quasi-steady states continuing longer than 5-year. Then, in order to identify the years when regime shifts occurred in the SST field, the time series of original gridded SST data and those of the EOF modes are carefully inspected. As a result, six regime shifts are detected in the study period from the 1910s to the 1990s: 1925/26, 1945/46, 1957/58, 1970/71, 1976/77 and 1988/89. It is ascertained that the shifts at almost all grids are completed within one year. All the regime shifts have similar SST and atmospheric circulation pattern including the changes in an intensity of the Aleutian Low (AL) and the corresponding SST changes in the central North Pacific. All the regime shifts can be described well by the combination of the first and the second EOF modes. Duration between each regime shift is about 10 years, which are identical to the PDO. The simultaneous shifts in the first and the second EOF modes imply that the change in the AL activity associated with the PNA pattern might have some connection with that of the AO.

In Chapter 3, the regime shifts previously identified in Chapter 2 over the Northern Hemisphere is investigated in relationship with tropical SST variation. It is found that SST averaged over the Nino 3.4 region (Nino 3.4 SST), which is known to be a good indicator of the ENSO, shows coherent changes with the regime shifts. The regression maps based on Nino 3.4 SST show typical El Nino condition. By subtracting the variations linearly correlated with Nino 3.4 SST from the raw SST field, the residual SST field is obtained. An EOF analysis shows a dominant mode of variations in the residual field that is confined to the mid- and high-latitude North Pacific, which is known as the North Pacific (NP) mode. Another dominant mode of variation corresponds to the AO.

All the regime shifts identified in Chapter 2 are detectable in the residual SST field. Most of the regime shifts (the 1925/26, 1945/46, 1957/58, 1970/71, and 1976/77 shifts) take place concurrently with the two aforementioned EOF

modes and changes in Nino 3.4 SST, while the 1988/89 shift is not associated with Nino 3.4 SST changes. This indicates that the regime shifts can be divided into the two groups: one is closely linked with the tropical Pacific and the Indian Ocean variations, and the other is independent of these tropical variations

In Chapter 4, the analysis domain is extended into the global ocean. Investigation is also made to all around the year including summer in Northern Hemisphere, and seasonal evolution of the regime shifts is described. Tropical variations are more specifically caught as the El Nino. As a result, it is found that significant changes of mean state widely appeared in the global SST anomaly field have happened five times from the 1910s to the 1990s: 1925, 1942, 1957, 1970 and 1976. Since the change regions spread over both hemispheres and/or multiple oceanic basins, they can be considered as 'the global regime shifts' . The years of regime shifts are consistent with those of the Northern Hemisphere regime shifts including the tropical variations that are described in Chapter 3.

It is also shown that the regime shifts have happened concurrently with the ENSO events, which seems that the ENSO event plays as a trigger of the regime shift. At the regime shift, the tropical Pacific SSTs change from La Nina (El Nino) to El Nino (La Nina) conditions within one year. Further, the ENSO events just after the regime shifts begin in the JAS (July to September) season and reach the mature phase in the JFM (January to March) season as a typical evolution of the ENSO events. After that, they continue to at least the next year.

Five regime shifts detected have similar features with each other in the seasonal evolution and persistence of signals. First, the shifts start in the JAS season: SST change occurs in the eastern and central tropical Pacific, and change in the mid-latitudes of the North and South Pacific appears with the opposite sign. Then the shifts in the JFM season are followed. The spatial patterns are similar to those of the JAS season, but signals in the North Pacific become remarkable. These features resemble those corresponding to a series of evolution of the ENSO events, but the signals in the North Pacific and the North Atlantic are much stronger than those of the typical ENSO events. After the shifts happened, the spatial patterns of SST changes, which occurred at the regime shift, persist until the next shift. The persistence of signals is more prominent in the JFM season than in the JAS season.

From the reexamination of the dominant variation modes in the global SSTs using the EOF analyses, four modes are identified: the ENSO mode, the Southern Hemisphere trend mode, the NP mode, and the AO mode. At the years when regime shifts occur, the ENSO mode, the NP mode, and the AO mode show significant concurrent phase reversals in the global scale as in the Northern Hemisphere as shown in Chapter 3. These findings might give the reason why SST changes at the regime shift are similar but not exactly the same pattern as that of the ENSO. Furthermore, it can be considered that simultaneous phase reversal of the NP mode would suppress the growth of anticyclonic (or cyclonic) circulation in the atmosphere over the western tropical Pacific. This suggests that the ENSO event, which begins with the regime shift, would not reverse its condition and last for the following several seasons.

In Chapter 5, conclusions of the present study are presented. Careful examination of the SST field instead of usage of indices enables to identify years of the regime shifts that have not perfectly identical spatial patterns with each other. It also permits the discussion about similarity and difference between the regime shifts. As a result of the present study, a whole picture of the regime shift is resolved, and its physical interpretation is given. The present study will also give a useful guidance to understand fluctuations of oceanic resources in the oceanic ecosystem.

論文審査の結果の要旨

気候は，様々な周期的変動の他に，ある状態から別の状態へと急変することが知られている．これを気候ジャンプ，あるいはレジームシフトと呼ぶ。安中さやか提出の論文は，このレジームシフトがいつ起こり，その前後で大気循環場にどのような変化が起こったのかを，海面水温（SST）場と，気圧場や風の場などから明らかにすることを目的としたものである。

まず，1910年代から1990年代を対象とし，北半球冬季（1 - 3月期）に起こったレジームシフトの同定を試みた。その結果， 期間中6回のシフトが見出された。すなわち，1925/26年，1945/46年，1957/58年，1970/71年，1976/77年，1988/89年のシフトである。これら6回のレジームシフトは1年以内にシフトを完了し，すべてアリューシャン低気圧と北太平洋中央部のSSTの変化を伴っていることがわかった。また，これらのシフトは，太平洋北米パターンに伴うSST場のEOF第1モードと，北極振動に伴う第2モードの組み合わせで記述できることもわかった。

次に，レジームシフトと熱帯域におけるSST変動との関係を調べた。その結果，熱帯太平洋中央部のSSTは，レジームシフトに連動して変化していることがわかった。すなわち，ほとんどのシフトはNino 3.4域の SST の変化と同期して発生しており，1988/89年のシフトのみが Nino 3.4 SSTの変化とは無関係であった。また，先に同定された6つのレジームシフトすべてが，熱帯のSST変動とは線形独立な残差SST場においても，検出されることが確認された。

さらに，南半球も含めた全球海洋を対象とし，また，1−3月期に加えて、7−9月期に関する解析も行った。その結果，北半球冬季に見出されたレジームシフトのうち，熱帯変動を伴う5回のシフトは全球スケールで起こっていたこと，そしてENSOイベントの発生と同期して起こっていたことがわかった。また，レジームシフトに伴うSSTの変化は，ENSOイベントに伴うものと比べ，1−3月期の北太平洋や北大西洋において顕著であり，その状態はほとんどの海域で次のレジームシフトまで持続していることが見出された。また，全球SST場の卓越モードである ENSOモード，北太平洋モード，北極振動モードが，レジームシフトと同期して位相反転を起こしていることもわかった。

以上のように本論文は，全球のSST場を対象として20世紀に起こったレジームシフトと対応する大気循環場の変化を詳細に解析し，多くの新知見を得ており，本人が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって，安中さやか提出の博士論文は，博士（理学）の学位論文として合格と認める。