OCEAN-ATMOSPHERE INTERACTION AND TROPICAL CLIMATE

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Contents

Summary

The ocean and atmosphere are in constant exchange of heat, water, and momentum. The interaction of the ocean and atmosphere adds shades and rhythms in the structure of tropical climate. Ocean-atmosphere interaction research has experienced rapid growth in studying El Nino/Southern Oscillation (ENSO), and yielded tremendous societal benefits by enabling and improving the prediction of ENSO and important modes of climate variability. This chapter reviews major ocean-atmospheric feedbacks that give rise to ENSO and other variations in tropical climate.

1. Introduction

Solar radiation is the ultimate source of energy for motions in the atmosphere and ocean. Most absorption of solar radiation takes place on the Earth surface, the majority of which is occupied by oceans. Thus oceanic conditions, sea surface temperature (SST) in particular, are important for atmospheric temperature conditions and circulation. Fueled by water vapor evaporated from the surface, deep convection in cumulonimbus clouds and resultant condensation and freezing are the dominant mechanism for heating the atmosphere. Atmospheric convection is strongly regulated by SST on the one hand and affects the ocean on the other by modulating surface momentum and heat fluxes. Latent heating in atmospheric convection drives surface winds and modulates cloud cover. Surface winds drive ocean circulation and affect ocean surface heat flux while clouds modulate surface radiative flux.

Thus, the ocean and atmosphere are a coupled system and their interaction helps shape tropical climate and its variability. Examples are abundant. Figure 1a shows the climatology of precipitation and SST. While the annual-mean solar radiation at the top of the atmosphere (TOA) is zonally uniform and symmetric about the equator, rainfall and SST are highly asymmetric both in the east-west and north-south directions. On the equator, SST in the eastern Pacific (say, near the Galapagos Islands, 90^{o}W, equator) features a pronounced annual cycle with the maximum in March (Figure. 2) despite a TOA solar radiation dominated by a semi-annual cycle. Such departures in space and time from the solar radiation distribution are the result of ocean-atmosphere interaction.

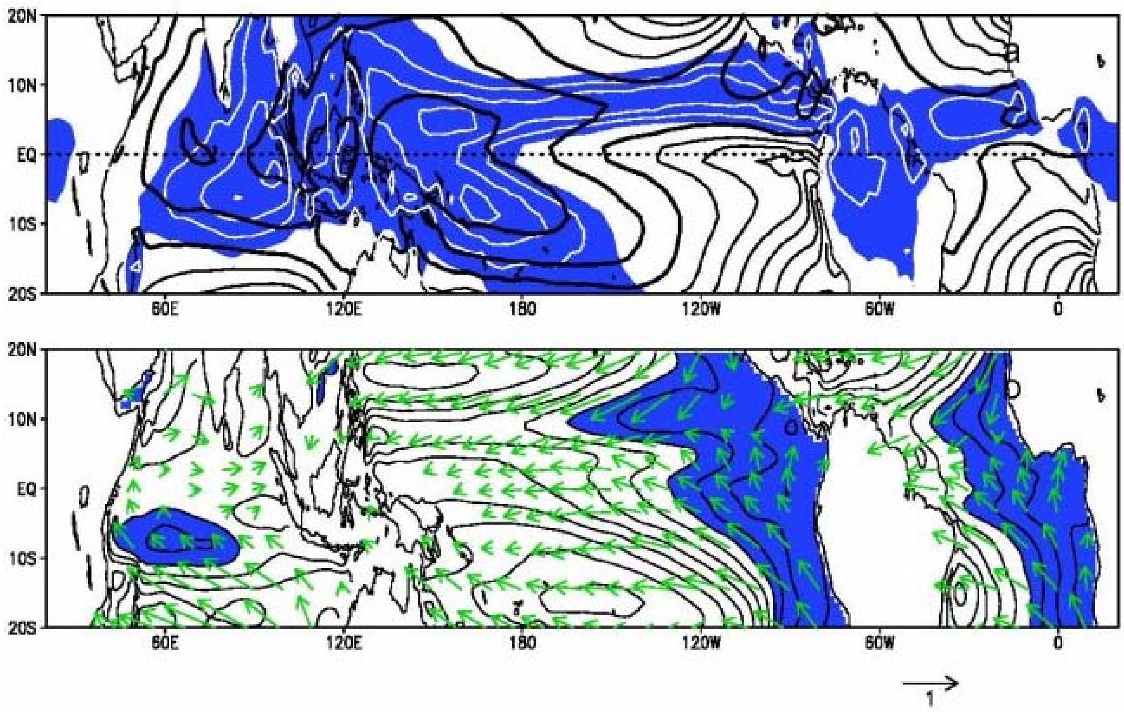

Figure 1. Annual-mean climatology: (a) SST (black contours at 1°C intervals; contours of SST greater than 27°C thickened) and precipitation (white contours at 2 mm/day; shade > 4 mm/day); (b) surface wind stress vectors (Nm^{-2}) and the 20°C isotherm depth (contours at 20 m intervals; shade < 100 m).

This Topic concerns major ocean-atmospheric feedbacks important for spatial and temporal variations of tropical climate. They involve changes in cloud cover, surface evaporation, and ocean dynamical adjustments. The scope of this review is limited to ocean-atmosphere interaction operating on large (>100 km) spatial and long (> 1 week) temporal scales. While variability on weather and shorter timescales and beyond the instrumental record is not covered, the feedback mechanisms discussed here are expected to operate for paleoclimate variability (Chiang et al. 2003; Timmermann et al. 2007) and future climate change (Vecchi and Soden 2007). For a more comprehensive discussion of ocean-atmosphere interaction and its applications, readers are referred to a recent monograph on this topic (Wang et al. 2004).

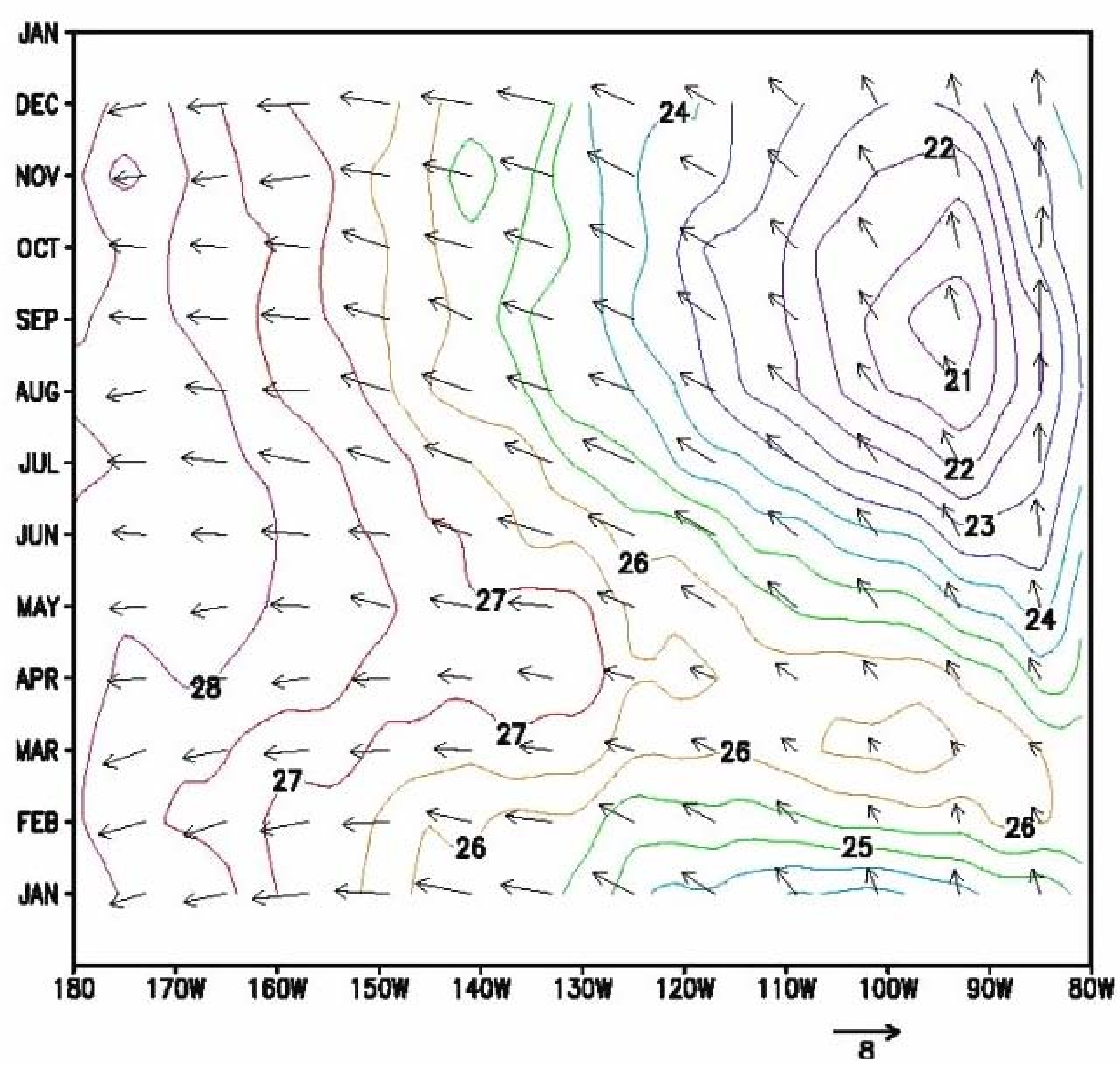

Figure 2. Seasonal cycle in the equatorial Pacific: SST (contours in °C) and surface wind velocity (vectors in m/s).

2. Bjerknes Feedback

Strong east-west asymmetry is found over the equatorial Pacific, characterized by the Walker circulation (with the easterly winds at the surface) in the atmosphere and the cold tongue in SST (Figure. 1a). To a lesser extent, similar asymmetry is observed over the equatorial Atlantic.

Under easterly winds, surface ocean currents flow poleward a few degrees away from the equator following the Ekman dynamics. The divergence of these poleward Ekman flows requires water to upwell into the surface layer on the equator. If the thermocline is close to the surface, this equatorial upwelling brings the cold thermocline water into the mixed layer, causing an SST cooling. On the equator where the Coriolis force vanishes, surface ocean currents flow in the wind direction, resulting in the westward South Equatorial Current (SEC) in the Pacific and Atlantic. The equatorial upwelling and the westward (SEC) shoals the thermocline in the east and deepens it in the west (Figure. 1b). In steady state on the equator, the easterly wind stress is nearly balanced by the pressure gradient force associated with the eastward shoaling of the thermocline.

From an oceanographic point of the view, the easterly winds shoal the thermocline eastward and induce the equatorial upwelling, keeping the eastern basin cool. From a meteorological point of the view, on the other hand, the eastward SST cooling limits deep convection to the west and maintains a sea pressure gradient that drives the easterly winds along the equator. This circular argument indicates that ocean-atmosphere interaction is at the heart of the cold tongue formation.

The feedback may be described as follows (Figure. 3). Let us begin with modest easterly winds over the equatorial Pacific, which induce upwelling and tilt the thermocline, both acting to cool the eastern ocean and suppressing atmospheric convection there. This reduction in deep convection in the east raises sea level pressure, intensifying the initial easterly winds at the surface. The amplification of the initial perturbation indicates a positive feedback resulting from ocean-atmosphere interaction.

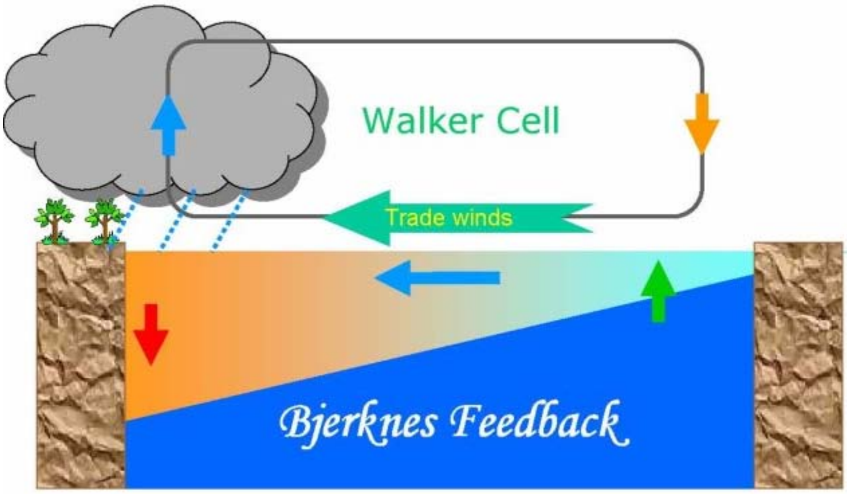

Figure 3. Schematic for Bjerknes feedback.

Bjerknes (1969) first proposed this feedback hypothesis for El Nino/the Southern Oscillation (ENSO), to which Wyrtki (1975) added the thermocline adjustment. Therefore it is also called the Bjerknes-Wyrtki feedback. The thermocline depth in the eastern Pacific controls how much equatorial upwelling cools SST, and is determined by the transport of warm upper-ocean water above the thermocline between the east and west, and in and out of the equatorial belt. Such warm water transport, governed by large-scale ocean wave dynamics, is essential for ENSO (see Topic xx in this Theme). In coupled ocean-atmosphere models, the most unstable or least damped mode often displays an interannual cycle of SST warming and cooling in the eastern basin, with the deepening and shoaling of the thermocline, respectively. Besides ENSO, such a Bjerknes mode of coupled ocean-atmospheric variability is observed in the equatorial Atlantic and Indian Oceans on interannual timescales (Chang et al. 2006).

The equatorial cold tongue displays annual expansion and retreat in July-September and February-April (Figure. 2), respectively, over the Pacific and Atlantic. This annual cycle in SST is forced by that in meridional wind superimposed on the annual-mean southerly cross-equatorial winds, the latter being part of meridional climatic asymmetry. During

July-September, the southerlies intensify in response to the seasonal warming (cooling) in the Northern (Southern) Hemisphere, enhancing the upwelling cooling in the equatorial belt (Mitchell and Wallace 1992). Conversely, the relaxed southerlies cause equatorial SST to warm up during February-April. Unlike ENSO, thermocline adjustments are of a secondary importance for the annual cycle but the interaction of SST and surface winds causes a westward phase propagation of the annual cycle.

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Biographical Sketch

Shang-Ping Xie received B.Sc. from Shandong College of Oceanography, China in 1984 and Ph.D. from Tohoku University, Japan in 1991. He was on the faculty of Hokkaido University, Japan and is currently professor at University of Hawaii, where he leads Indo-Pacific ocean climate research at the International Pacific Research Center. He is editor of Journal of Climate. He received the Yamamoto-Shyono and Society Medals from the Meteorological Society of Japan in recognition of his contributions to ocean-atmosphere interaction and climate research. He was a contributing author for the third assessment report of the Intergovernmental Panel for Climate Change, a scientific body that won the 2007 Nobel Peace Prize. His interests include climate formation, variability, and change, especially the role of ocean-atmosphere.