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Subtropical gyre variability observed by ocean-color satellites

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Abstract

The subtropical gyres of the world are extensive, coherent regions that occupy about 40% of the surface of the earth. Once thought to be homogeneous and static habitats, there is increasing evidence that mid-latitude gyres exhibit substantial physical and biological variability on a variety of time scales. While biological productivity within these oligotrophic regions may be relatively small, their immense size makes their total contribution significant. Global distributions of dynamic height derived from satellite altimeter data, and chlorophyll concentration derived from satellite ocean-color data, show that the dynamic center of the gyres, the region of maximum dynamic height where the pycnocline is deepest, does not coincide with the region of minimum chlorophyll concentration. The physical and biological processes by which this distribution of ocean properties is maintained, and the spatial and temporal scales of variability associated with these processes, are analyzed using global surface chlorophyll-*a* concentrations, sea-surface height, sea-surface temperature, surface winds from operational satellite and meteorological sources, and hydrographic data from climatologies and individual surveys. Seasonal and interannual variability in the areal extent of the subtropical gyres are examined using 8 months (November 1996–June 1997) of Ocean-color and Temperature Sensor (OCTS) and 6 years (September 1997–October 03) of Sea-viewing Wide Field-of-View Sensor (SeaWiFS) ocean-color data. The ocean-color data are interpreted in the context of climate variability and measured changes in other ocean properties (i.e. wind forcing, surface currents, Ekman pumping, and vertical mixing). The oligotrophic waters of the North Pacific and North Atlantic gyres are observed to be expanding over this period, while those of the South Pacific, South Atlantic, and South Indian Ocean gyres show much weaker and less consistent tendencies.
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1. Introduction

The subtropical gyres of the world are extensive, coherent regions that occupy ~40% of the surface of the earth. The upper kilometer of the subtropical gyres is primarily wind driven (Huang and Russell, 1994). The horizontal and vertical motion in this layer plays a significant role in controlling the interaction between the atmosphere and ocean, which is of vital importance to our understanding of the oceanic general circulation and climate (Huang and Qiu, 1994). The gyres are characterized by a deep pycnocline at their centers and strong horizontal gradients of temperature (T) and salinity (S) at the fringes due to pycnocline outcropping. The flow in the western limbs (western boundary currents) is intensified by the latitudinal changes of the Coriolis acceleration (β effect), while the flow is relatively weak in the gyres' eastern parts. The broad region of relatively weak flow occupies most of the gyre and is called the Sverdrup regime (Pedlosky, 1990). The dynamic center of the gyres can be identified by a maximum sea-surface height (SSH). The pycnocline shoals in the mid-latitudes, where isopycnals outcrop at the Subtropical Front (STF), and at the equator, where Ekman flow divergence promotes upwelling.

While nutrients can be supplied to the euphotic zone through a number of processes, e.g., Ekman upwelling, eddy upwelling (McGillicuddy et al.,

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1998), convective overturning and mixing, and horizontal advection, the interior zones of the subtropical gyres are regions where nutrient supply is minimal and concentrations of nutrients and biomass are relatively low throughout the year. While biological productivity within the oligotrophic regions of the gyres may be relatively small (Hayward, 1987; Hayward, 1991; Jenkins and Goldman, 1985; Jones et al., 1996; Karl et al., 1996), their immense size makes their total contribution significant. An important biological characteristic of the subtropical gyres is the large variability in phytoplankton growth rates with minimal changes in biomass (Laws et al., 1987; Marañón et al., 2000; Marañón et al., 2003; Marra and Heinemann, 1987). Understanding the interactions between physical and biological processes within the subtropical gyres is central for determining the magnitude and variability of the carbon exported from the surface to the deep ocean.

Once thought to be homogeneous and static habitats, there is increasing evidence that subtropical gyres exhibit substantial physical and biological variability on a variety of time scales (Karl and Lukas, 1996; Karstensen and Quadfasel, 2002; Levitus, 1989; Yasuda and Kitamura, 2003). Ecosystem indicators in the subtropical gyres, such as biomass, chlorophyll-*a* (chl-*a*) concentration, and new and export productions, respond to climate variability (Karl et al., 2001; Oschlies, 2001). This physical–biological coupling between the climate cycles, e.g., El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO) and the Antarctic Circumpolar Wave (ACW), and ecosystem dynamics is a consequence of altered nutrient flux pathways that result from changes in the stratification and circulation of the subtropical gyres. Climate-induced variations in community structure and biogeochemical processes of the North Pacific subtropical gyre (Karl et al., 2001) and the North Atlantic (Bates, 2001; Ottersen et al., 2001) have been linked to the PDO and NAO, respectively.

This paper examines five major gyre systems, i.e. the North and South Pacific, the North and South Atlantic, and the southern Indian Ocean, and provides brief initial analyses of the relationship between gyre physics (dynamics and hydrographic structure) and surface biology. The analyses are based on satellite ocean-color imagery, the seasonal cycle of forcing and upper-ocean phytoplankton response within the gyres, and the observed interannual trends in the oligotrophic gyre spatial extents and mean chl-*a* concentrations. Some inferences regarding the couplings between the gyre ecosystems and physical forcings (circulation, hydrography, and climate variability) are suggested, but more definitive discussions will need to be based on longer satellite ocean-color time series, modeling studies, and more extensive in situ data sets.

4. Conclusions

The dynamic and biological gyre centers are not collocated. The location of the minimum chlorophyll concentration is a better indicator of the maximum nutricline depth than the location of the maximum dynamic height. Within the biological center of the gyres, photoadaptation is the most probable mechanism for chl-*a* enhancement during winter because nutrient renewal in the euphotic zone is limited due to the nutriclines being much deeper than the mixed layer.

The 7-year time series of ocean-color from OCTS and SeaWiFS data reveal large seasonal variability in the extent of the low chlorophyll regions of the gyres. Vertical mixing, Ekman pumping, thermocline displacement, and lateral fluxes are the main driving mechanisms for the observed seasonal changes in chlorophyll concentration.

The Indian Ocean subtropical gyre has a unique seasonal behavior in response to physical forcing. The chl-*a* concentration increases with downwelling intensification. The increase in chl-*a* coincides with the northward migration of the subtropical front in austral winter, which increases the transport of nutrients to the gyre region.

Systematic trends in chl-*a* distribution suggest that the northern hemisphere gyres are expanding and becoming more oligotrophic, while the trends in the southern hemisphere gyres are weaker and less consistent. Although the available ocean-color record is still too short to unambiguously relate these trends in biomass to climate variability, some consistent dynamic patterns related to known climate cycles (PDO, NAO, ACW) are beginning to emerge. A longer ocean record ($\sim$10 years) will be required to establish a more concrete correlation between the long-term variability of the subtropical gyres and climate trends. The exact nature of the couplings will require modeling studies in addition to the collection and analysis of longer satellite and in situ data records. The satellite data analyses presented here are possible because of the unprecedented stability of the SeaWiFS time series, which is due to the use of monthly lunar calibrations and is totally independent from the Earth-viewing data. The analyses presented herein are intended to simply highlight the possible connections between biological and physical variability in the subtropical gyres on seasonal and interannual time scales.