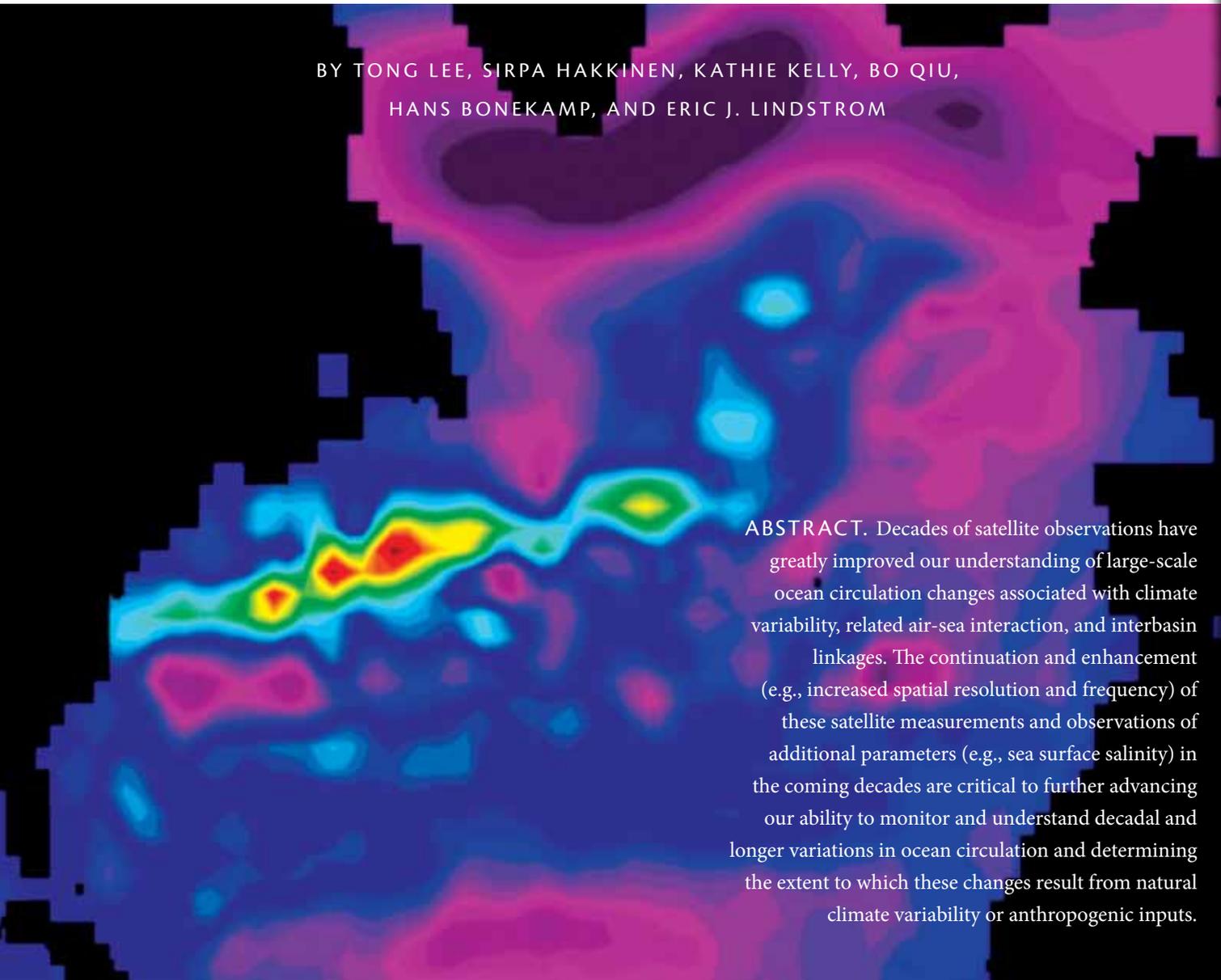


SATELLITE OBSERVATIONS OF OCEAN CIRCULATION CHANGES ASSOCIATED WITH CLIMATE VARIABILITY

BY TONG LEE, SIRPA HAKKINEN, KATHIE KELLY, BO QIU,
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ABSTRACT. Decades of satellite observations have greatly improved our understanding of large-scale ocean circulation changes associated with climate variability, related air-sea interaction, and interbasin linkages. The continuation and enhancement (e.g., increased spatial resolution and frequency) of these satellite measurements and observations of additional parameters (e.g., sea surface salinity) in the coming decades are critical to further advancing our ability to monitor and understand decadal and longer variations in ocean circulation and determining the extent to which these changes result from natural climate variability or anthropogenic inputs.

“ SATELLITE OBSERVATIONS HAVE SIGNIFICANTLY ADVANCED OUR KNOWLEDGE OF THE OCEAN CIRCULATION VARIABILITY IN RELATION TO VARIOUS MODES OF CLIMATE FLUCTUATIONS...” ”

INTRODUCTION

Ocean circulation distributes heat, freshwater, and carbon within the ocean. This distribution affects air-sea fluxes and influences ocean-atmosphere interaction associated with climate variability and change. Understanding the role ocean circulation plays in climate variability requires systematic measurements of the global ocean over long time periods (e.g., decadal and longer) with relatively uniform spatio-temporal sampling. In situ data alone are inadequate to study many aspects of large-scale changes in ocean circulation because of limited durations and relatively sparse sampling. With their near-uniform sampling in space and time and (often) global coverage, satellite observations have become critical to the monitoring and understanding of global ocean circulation and its relationship to climate variability.

Satellite observations have significantly advanced our knowledge of the ocean circulation variability in relation to various modes of climate fluctuations, such as the El Niño-Southern Oscillation (ENSO), Indian Ocean Zonal/Dipole Mode (IOZDM), North Atlantic Oscillation (NAO), Southern Annual

Mode (SAM), and Pacific Decadal Oscillation (PDO). For example, nearly two decades of global scatterometer measurements of wind stress have revolutionized our ability to diagnose dynamical forcing of ocean circulation (Bourassa et al., 2010), in particular, because they permit more accurate estimates of wind stress curl compared to estimates derived from sparse in situ measurements (Chelton and Xie, 2010). Altimeter measurements of sea surface height, also available for nearly two decades, have provided a detailed view of propagating signals in the ocean associated with planetary waves and eddies in addition to a nearly global view of the structure of large-scale circulations (Fu et al., 2010). These advances are far too broad to be summarized in a short paper. Here, we only highlight some examples of scientific accomplishments enabled by satellite observations in detecting and understanding ocean circulation changes associated with climate variability. These highlights, described in the next section, include satellite-based observational studies of large-scale meridional overturning circulation (MOC) and horizontal gyre circulation in the Pacific, Atlantic, and Indian oceans,

which are main mechanisms of property transport in the ocean associated with various modes of climate variability. They illustrate satellites' unique vantage point for observing the global ocean in ways that are complementary to in situ observing systems. After that, we discuss areas in which satellite observations are expected to have significant impacts, especially in terms of decadal variability, in the coming decades. We also describe strategies for determining observational requirements related to these areas.

OCEAN CIRCULATION CHANGES ASSOCIATED WITH CLIMATE VARIABILITY North Atlantic Subpolar Gyre and AMOC

The Atlantic Meridional Overturning Circulation (AMOC) is believed to affect the climate of Europe and North America by carrying warm, saline subtropical upper-ocean waters to the subpolar region (the upper limb of AMOC) and releasing the heat to the atmosphere during wintertime. The resultant cooling causes the waters to sink to great depths, where they return southward as the lower limb of AMOC. AMOC's state is closely linked

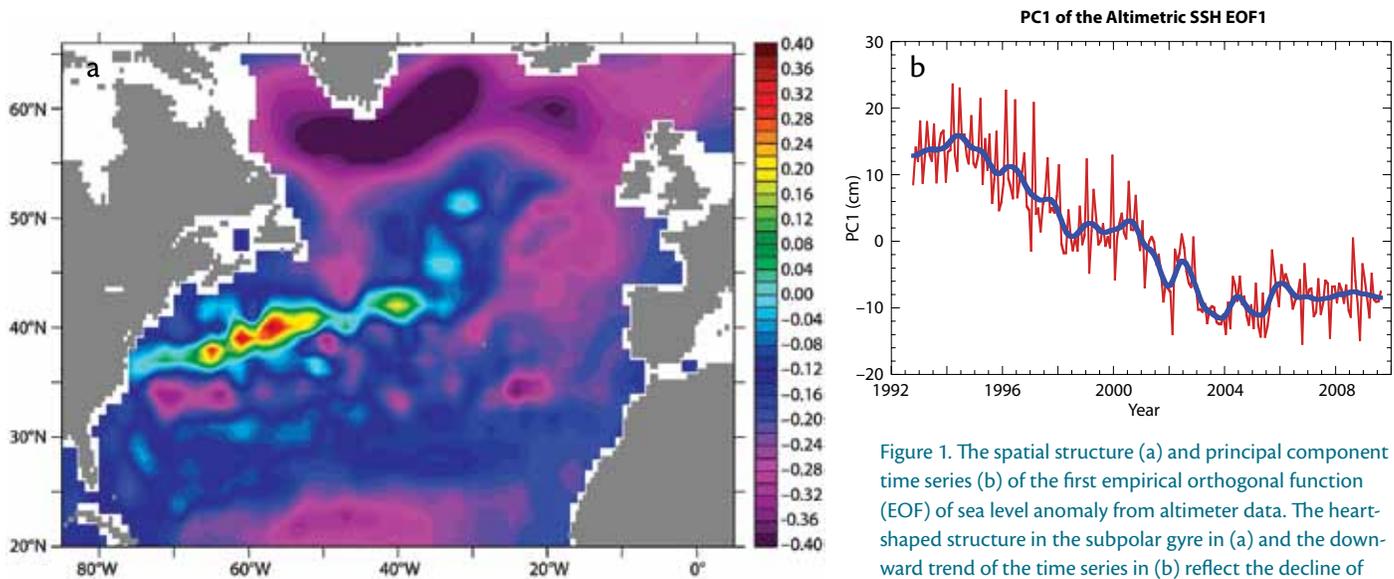


Figure 1. The spatial structure (a) and principal component time series (b) of the first empirical orthogonal function (EOF) of sea level anomaly from altimeter data. The heart-shaped structure in the subpolar gyre in (a) and the downward trend of the time series in (b) reflect the decline of the subpolar gyre. After Hakkinen and Rhines (2005, 2009)

to the dynamics of the North Atlantic subpolar gyre because the latter affects the salinity and thus the stability of the water column that influences the “sinking” branch of AMOC (Hakkinen, 2002; Hátún et al., 2005). Although the meridional circulation associated with AMOC is the dominant mechanism of meridional heat transport (MHT) in the subtropical ocean, it is not the major contributor to MHT in the subpolar region because the vertical temperature gradient reduces substantially from the subtropical to the subpolar ocean. In the subpolar region, the horizontal gyre becomes important in maintaining MHT (Volkov et al., 2008).

The North Atlantic subpolar gyre is associated with a depression of sea surface height (SSH) that reflects the mean cyclonic circulation (by geostrophic theory). Hakkinen and Rhines (2004, 2009), using SSH anomaly observations obtained from satellite altimeters, revealed substantial decadal changes in the subpolar gyre over the past couple of decades. They showed that SSH in the center of the subpolar gyre increased during the 1990s (Figure 1). This SSH increase implies an anomalous anticyclonic flow that weakens the subpolar gyre. They also analyzed local surface forcing and concluded that buoyancy forcing has a dynamic effect

that is consistent with altimetric and hydrographic observations—a weak thermohaline forcing allows relaxation of the domed structure of the isopycnals associated with the subpolar gyre and thus weakens the gyre. After 2004, however, the subpolar gyre’s strength stabilized (Figure 1).

Hakkinen and Rhines (2009) also discussed another contribution to subpolar SSH changes: increased penetration of warm, saline subtropical waters into the subpolar gyre after 2001. This major climate shift is evident in Northeast Atlantic hydrographic measurements (the Ellett Line across the Rockall Trough), which recorded the warmest and most saline conditions there after 2001 since the repeatedly occupied hydrography line was established in 1975 (<http://www.noc.soton.ac.uk/obe/PROJECTS/EEL/latestresults.php>). The salinization source is evident in circulation changes observed from surface drifter tracks (from the NOAA Global Drifter Program; Hakkinen and Rhines, 2009).

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The drifters deployed in the subtropics passed through the Gulf Stream region, followed the southward branch of the North Atlantic Current (NAC), and tracked the clockwise subtropical circulation until around the year 2000. After 2001, the drifter tracks turned northeastward in the eastern basin. The abrupt change in eastern basin circulation around 2000 is detectable in the eddy kinetic energy computed from altimetric geostrophic velocities in the subpolar latitudes. This northeastward shift of surface currents is still active; the Ellett Line salinity time series shows continued saline conditions through 2009 (Hakkinen and Rhines, 2009).

Both the weakened subpolar gyre circulation and the changes in the hydrography could reflect changes in AMOC. Furthermore, about once a decade, the wintertime deep convection in the western subpolar gyre that can affect AMOC is disrupted for several years. These events can be identified by upper-ocean freshwater, with an apparent advection of fresh surface waters from the Labrador Sea toward the east (Reverdin et al., 1997; Belkin et al., 1998). These fresh events are attributed to several different processes: excess ice outflow from the Arctic (mainly via the Fram Strait to the Denmark Strait), freshwater outflow (particularly through the Canadian archipelago), and potentially a weakened AMOC (bringing less salt northward). The associated salinity anomalies are typically 0.4–1 psu, which is within the resolution of the upcoming Aquarius satellite mission that will measure sea surface salinity (Lagerloef et al., 2008). The Aquarius satellite mission may contribute to the understanding of the relationship

between AMOC and salinity variability, for instance, by determining whether surface salinity is a passive tracer for AMOC changes or an active contributor to the dynamics (Hakkinen, 2002; Frankignoul et al., 2009).

AMOC's upper limb feeds warm, saline waters to the Nordic seas and to the west of Greenland toward Baffin Bay. The branch that flows into Baffin Bay has been linked recently to the warm-water invasion to the base of the Jakobshavn outlet glacier and its retreat (Holland et al., 2008). This invasion of warm waters appeared to have occurred in 1997, and warm conditions continued at least through 2006 (last published data). The NASA airborne laser altimetry surveys of Greenland outlet glaciers show that the Jakobshavn glacier speeds started to increase after 1997 associated with decreasing glacier surface elevation (Thomas et al., 2006). Changes in the AMOC upper limb may also have profound effects on the other outlet glaciers around southern Greenland (Thomas et al., 2009; Straneo et al., 2010). These observations again point to the importance of future space-borne salinity measurements in the study of AMOC and its associated impacts.

Connectivity of North Atlantic Subtropical and Subpolar Circulations

Between 50°W and 40°W, the Gulf Stream splits into a southeastward flow that recirculates to form the subtropical gyre and the northward-flowing NAC, which carries subtropical waters into the subpolar gyre. Continuity of the flow between the gyres has been questioned based on both surface and subsurface measurements: subsurface

floats have shown discontinuities at the gyre boundary (Lavender et al., 2000; Brambilla and Talley, 2006). Kelly and Thompson (2009), using observations from satellite altimeters, show that interannual increases in the Gulf Stream's strength correspond to increases in the subpolar gyre's recirculating flow, but not to increases in the NAC, a result that also suggests a lack of continuity of flow between gyres. Interannual changes in the path and the strength of the NAC are also found to be uncorrelated with Gulf Stream variability (Kelly and Thompson, 2009).

Oceanic throughflow of heat from the Gulf Stream to the NAC is a small fraction of the heat transported by the Florida Current into the subtropical gyre, where much of the heat is either stored locally or is fluxed to the atmosphere. The mid-latitude "baton pass" of heat from ocean to atmosphere that enhances northward atmospheric heat transport (Trenberth and Caron, 2001) and local heat storage may have as large a climate impact as AMOC. Increased heat storage south of the Gulf Stream is associated with a decrease in the volume of the isothermal layer of subtropical mode water (STMW; Hanawa and Talley, 2001; Kwon, 2003), which integrates both ocean and atmospheric forcing and therefore contributes to climate memory. Heat transported by the Gulf Stream, for which velocities can exceed 3 m s^{-1} , as well as local heat storage, makes air-sea interaction in this region markedly different from that of the ocean interior, where upper-ocean heat content is determined primarily by air-sea fluxes (Barsugli and Battisti, 1998). Gulf Stream heat transport anomalies force changes in heat storage (Dong and Kelly, 2004),

which in turn force anomalies in air-sea heat exchange; heat loss over the Gulf Stream lags an increase in heat storage by three months (Kelly et al., 2010). Kelly et al. (2010) estimated anomalies in both Gulf Stream circulation and heat storage from the 15-year satellite altimeter data record in conjunction with in situ observations such as Argo (<http://www.argo.ucsd.edu>). Ocean heat content in the upper few hundred meters has been shown to be a better climate predictor than sea surface temperature (SST) because its anomalies persist beyond the seasonal heating cycle (Deser et al., 2003). The possibility of a coupled response remains an unresolved issue for mid-latitude air-sea interaction, as discussed by Kwon et al. (2010).

The ocean loses heat to the atmosphere over the Gulf Stream at an annual average rate exceeding 100 W m^{-2} through turbulent exchanges that fuel intense cyclogenesis (Hoskins and Hodges, 2002). The effect of the strong SST front on the overlying atmosphere's stability is reflected in winds over the

Gulf Stream measured by scatterometers (Chelton et al., 2004). Large SST anomalies can be caused by variability in both the Gulf Stream path latitude and the strength of surface currents. Indices of these two sources of variability have been created by zonally averaging altimeter-derived estimates of path latitude and SSH difference across the Gulf Stream, respectively. A linear regression of SST against each index quantified their effect on SST (Figure 2). High-resolution heat flux fields that are derived primarily from satellite observations of SST and surface winds reveal the effects of the Gulf Stream front on latent and sensible fluxes. In addition, Minobe et al. (2008) showed a deep tropospheric response to the Gulf Stream. Variations in Gulf Stream currents, air-sea heat fluxes, and storms have been shown to be related to NAO (Joyce et al., 2000; DiNezio et al., 2009).

Satellite data not only provide insights about cross-gyre exchange and mid-latitude air-sea interaction but also are an important part of the effort to monitor

AMOC in the subtropics and near the gyre boundary. Before the Gulf Stream leaves the coast, much of the variation in zonal pressure gradient that drives AMOC's upper limb is associated with density variations at the western and eastern boundaries (Cunningham et al., 2007; Cabanes et al., 2008). The transoceanic RAPID (Rapid Climate Change programme) mooring array was designed to monitor AMOC strength at these latitudes (near 26°N). Because Ekman transport is an important component of the total AMOC variability, satellite scatterometer data were routinely used along with in situ data from the RAPID array to estimate AMOC strength (Cunningham et al., 2007). After the Gulf Stream leaves the coast and becomes the NAC, the variation in zonal pressure gradient that forces AMOC's upper limb primarily occurs in the ocean's interior (as opposed to at its boundaries). Moreover, the steep topographic slope near NAC latitudes minimizes the area of the current that cannot be sampled by Argo floats (i.e., regions west of the NAC with depths less than about 2000 m). Capitalizing on these facts, Willis (2010) used satellite altimeter and Argo data (which do not sample the regions shallower than 2000 m) to infer changes in the strength of AMOC's upper limb near 40°N . The result suggested there was no reduction in AMOC's strength since the 1990s, as had been inferred from three synoptic hydrographic sections during this period (Bryden et al., 2005). AMOC strength exhibits large, high-frequency fluctuations (e.g., on time scales of days to months; e.g., Cunningham et al., 2007). A few studies (e.g., Wunsch and Heimbach, 2007; Balmaseda et al., 2007) discussed the difficulty

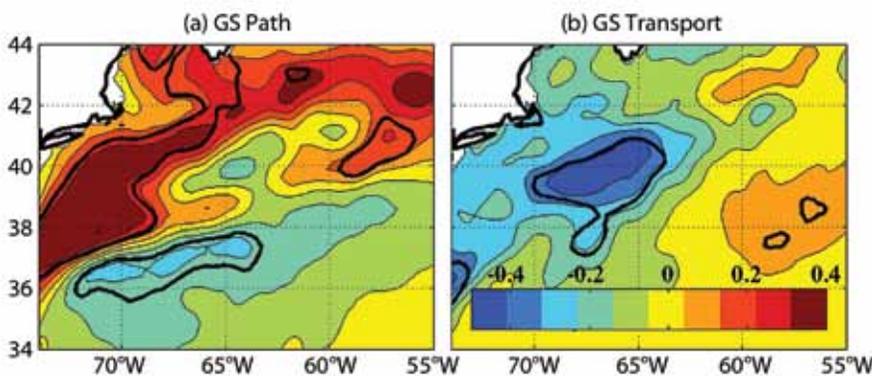


Figure 2. Sea surface temperature (SST) response to changes in path latitude (a) and transport (b) indices of the Gulf Stream (GS). SST anomalies were obtained by regression against zonally averaged ($50^\circ\text{--}70^\circ\text{W}$) changes in latitude and sea surface height difference across the Gulf Stream, as a measure of transport. Anomalies correspond to a one-standard deviation northward shift and increase in transport, respectively. Bold contours enclose regions where correlations between SST and indices are statistically significant. Color bar in (b) applies to both panels with units of degrees Celsius. Adapted from Kelly et al. (2010)

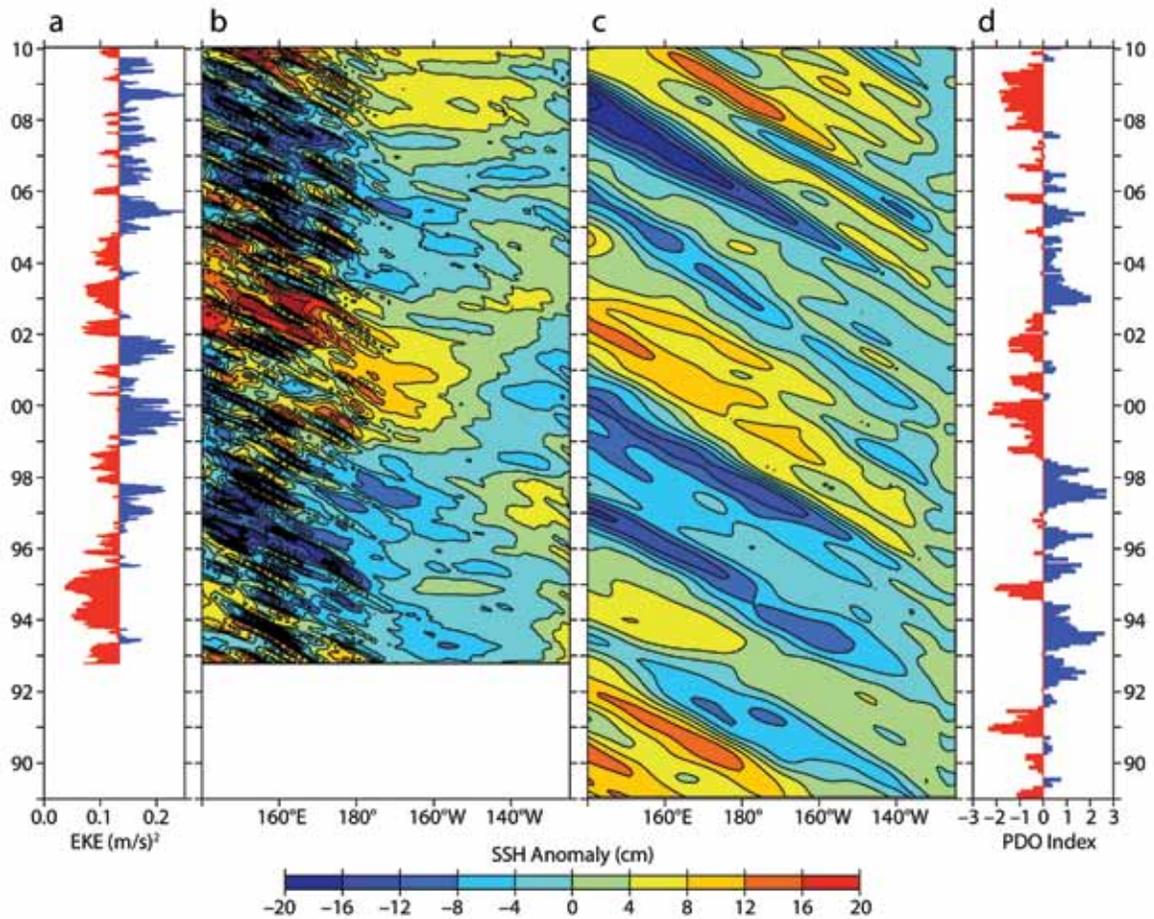


Figure 3. (a) Time series of eddy kinetic energy (EKE; deviation from time mean) in the upstream Kuroshio Extension region of 141°–153°E and 32°–38°N. Here, EKE is calculated using weekly SSH anomaly data by assuming geostrophy. For comparison with the PDO index, the time series is plotted as the deviation from the regional mean EKE value, 0.13 (m/s)². (b) SSH anomalies along the zonal band of 32°–34°N from satellite altimeter data. (c) Same as panel b but from the wind-forced baroclinic Rossby wave model. (d) PDO index from <http://jisao.washington.edu/pdo/PDO.latest>. Adapted from Qiu and Chen (2010)

in estimating low-frequency AMOC changes using infrequent samples of synoptic measurements.

North and South Pacific Gyre Circulations

In the Pacific sector, horizontal gyre circulations in mid- to high-latitude regions exhibit decadal variability that is associated with PDO and SAM. The advent of high-accuracy satellite altimetry in the early 1990s provided the research community with not only an additional tool to monitor the decadal changes of these mid- to high-latitude

circulations but also a means to explore their underlying dynamics.

With the dominant scales of spatial variability becoming smaller toward the higher latitudes, exploring mid-latitude ocean variability with traditional in situ measurements becomes more challenging. For example, although high mesoscale eddy variability has been detected in the Kuroshio Extension region of the subtropical North Pacific for a long time (e.g., Mizuno and White, 1983), an important new discovery from the satellite altimeter measurements of the past 17 years is that the level of eddy

variability associated with the Kuroshio Extension system varies on decadal time scales. Figure 3a shows a times series of eddy kinetic energy level in the Kuroshio Extension region. Qiu and Chen (2005, 2010) found that, reflecting the dynamic state of the Kuroshio Extension system, the eddy level was relatively low during the early to mid 1990s and early to mid 2000s, and relatively high during the mid 1990s to early 2000s and mid to late 2000s.

In addition to detecting low-frequency modulations, information based on satellite SSH data is also

essential for developing understanding of the dynamics responsible for the observed modulations. Figure 3d shows a PDO index time series (Mantua et al., 1997). A positive (negative) PDO index corresponds to an enhanced (weakened) Aleutian low-pressure system over the mid-latitude North Pacific basin. Analysis of lagged correlation reveals that the eddy kinetic energy level in the

Ekman convergence in this case results in regional, positive SSH anomalies near 160°W. SSH anomalies generated in the eastern North Pacific tend to propagate westward at the speed of baroclinic Rossby waves of $\sim 3.8 \text{ cm s}^{-1}$, taking four years to cross the basin to reach the Kuroshio Extension southeast of Japan. As they arrive southeast of Japan, the positive SSH anomalies intensify/

forcing, Figure 3c does not include any boundary-forced SSH signals. Model-data consistency improves in the eastern basin if such boundary-forced SSH signals are added (Fu and Qiu, 2002). The Rossby wave model captures well all of the large-scale SSH anomaly signals that change sign on decadal time scales. This quantitative comparison confirms the notion that incoming SSH anomaly signals generated by PDO-related wind forcing in the eastern North Pacific initiate the decadal Kuroshio Extension modulations detected by satellite altimeter data over the past 17 years.

It is important to emphasize that basin-scale wind forcing is also important for large-scale SSH changes in the South Pacific Ocean. The decadal South Pacific SSH changes in the 1990s were dominated by an increasing trend in the 30°–50°S band and a decreasing trend in the central South Pacific Ocean poleward of 50°S. Roemmich et al. (2007) attributed this trend to a spin-up of the subtropical South Pacific gyre (by about 15% of the time mean strength). Since 2002, there has been a reversal in both of these trends. Qiu and Chen (2006) used the same wind-driven Rossby wave model (of the North Pacific, but adapted for the mid-latitude South Pacific) to clarify the causes for the observed spatially varying SSH signals in the South Pacific Ocean. Accumulation of wind-forced SSH anomalies along Rossby wave characteristics was found to be important for both the linear trends in the 1990s and their reversals in recent years. In particular, the large-scale wind variability responsible for the mid-latitude ocean circulation spin-up/spin-down in the South Pacific Ocean is associated with the Southern Annular

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Kuroshio Extension lags the PDO index by four years. Figure 3b shows the SSH anomaly signals averaged in the latitudinal band of 32°–34°N in the North Pacific Ocean as a function of time and longitude. Qiu and Chen (2010) found the wind stress curl variability associated with PDO to be important in causing decadal SSH changes with the center of action around 160°W, which is where the Aleutian low- and Pacific high-pressure systems intersect and where the decadal wind stress curl forcing is the largest. Specifically, when the PDO index is positive, the Aleutian low intensifies and shifts southward, which generates negative SSH anomalies near 160°W in the eastern North Pacific through surface wind-stress-driven Ekman divergence. The opposite is true when the PDO index is negative: wind-induced

stabilize the Kuroshio Extension jet, suppressing regional mesoscale eddy variability. The reverse is true when the negative SSH anomalies arrive southeast of Japan (Qiu and Chen, 2010).

Baroclinic Rossby wave dynamics control large-scale, wind-induced SSH variability. Specifically, large-scale SSH changes can be hindcast by integrating the anomalous wind-stress curl forcing of Rossby wave characteristics along a latitude line from the eastern boundary. Figure 3c compares the time-longitude plot of the SSH anomaly field in the same 32°–34°N band from the linear Rossby wave model with monthly wind stress curl data from the National Centers For Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis. To emphasize the importance of interior-ocean wind

Mode. The latter is a predominantly atmospheric internal variability associated with nonseasonal fluctuations of air-pressure differences between Southern Hemisphere subpolar and mid-latitude regions (Thompson and Wallace, 2000).

Meridional Circulations in the Indo-Pacific Sector

Wind-driven, shallow MOCs in the Pacific and Indian oceans transport heat poleward by carrying warm surface water from the tropics to the subtropics, and colder pycnocline water from the subtropics to the tropics (McCreary and Lu, 1994). By regulating tropical upper-ocean heat content, these circulations affect ocean-atmosphere coupling in the tropics and thus climate variability (e.g., ENSO and PDO).

Studying these MOCs using in situ observations is difficult. In situ observations of wind are far too sparse to characterize the forcing of MOCs and to estimate the strength of their upper branches (meridional Ekman transport). In comparison, the potential of using in situ observations to monitor flow in lower MOC branches (pycnocline flow) is much more promising because the lower branches vary more slowly and have larger spatial scales than the upper branches. However, the lower branch of the Pacific MOC has a zonally nonuniform structure that is characterized by an interior and western-boundary pathway (Lee and Fukumori, 2003). Existing in situ observations (e.g., from Argo and expendable bathythermographs) can capture the interior pathway of the lower branch (interior pycnocline flows that have relatively larger spatial scales), but they are too sparse near the boundaries to capture the variability

of the western-boundary pycnocline flow (e.g., McPhaden and Zhang, 2002, 2004). In the Indian Ocean, the lack of basin-scale in situ observations poses a major difficulty in the study of its MOC (Schott, 2005).

Below, we highlight efforts to use measurements from satellite scatterometers (ERS and QuikSCAT) and altimeters (TOPEX/Poseidon and JASON-1) to address scientific questions related to Indo-Pacific MOCs: (1) How do the Pacific and Indian ocean MOCs vary on interannual-to-decadal time scales? (2) What are the corresponding forcing mechanisms (e.g., local vs. remote forcing)? (3) Is there any linkage between the Pacific and Indian ocean MOCs, and if so, what are the physical processes? (4) What is the zonal structure of the variability of meridional flows associated with MOCs?

Based on the Ekman relation, the zonal wind stress obtained from scatterometer data can be used to infer meridional Ekman transport variability (MOC upper branch). Based on the geostrophic relation, the SSH difference between the western and eastern boundary is used to infer net meridional geostrophic flow variability in the tropical pycnocline (Lee and Fukumori, 2003). This is possible because in the tropical ocean where much of the geostrophic flow is concentrated in the pycnocline (i.e., the so-called one-and-half layer system), the SSH difference between the two boundaries (being the inversely proportional to pycnocline depth difference between the boundaries) reflects the zonal pressure gradient that drives the net meridional geostrophic flow in the pycnocline layer integrated across a latitude (Lee and Fukumori 2003).

Zonal Structure of the Pacific MOC

The most conspicuous feature of the zonal structure of MOC variability in the Pacific Ocean concerns the western-boundary and interior pycnocline flows (Lee and Fukumori, 2003; Lee and McPhaden, 2008). For time mean, these flows reinforce each other in regulating tropical heat content because they both carry colder pycnocline waters towards the equator, a flow that is balanced by the poleward Ekman transport of warm surface waters. On interannual-to-decadal time scales, however, the western-boundary and interior pycnocline flow counteract each other, with the latter being more dominant (Lee and Fukumori, 2003). Sea level anomalies from altimeters vividly illustrate these changes because the SSH differences across low-latitude western-boundary currents (i.e., the Mindanao Current and New Guinea Coastal Undercurrent) are anticorrelated to the SSH differences across the ocean's interior (i.e., from the eastern edge of a western boundary current to the eastern boundary). The anticorrelated variability of western-boundary and interior pycnocline flows is the result of tropical gyre oscillation in the western Pacific caused by off-equatorial wind stress curl, which is clearly depicted by scatterometer observations.

Relation of the Pacific and Indian Ocean MOCs

Lee (2004) and Lee and McPhaden (2008) used scatterometer and altimeter data to show the strengthening (weakening) of the MOC in the Pacific (Indian) Ocean in the 1990s, and weakening (strengthening) from 2000 to 2006 (Figure 4). They also found that, on interannual-to-decadal time scales,

changes in the strength of the Pacific and Indian ocean MOCs are anticorrelated. They attributed this anticorrelation to both atmospheric and oceanic processes. For atmospheric processes, Walker circulation oscillation leads to anticorrelated variability of the trade winds over both oceans and thus anticorrelated variations in poleward Ekman transports in the two oceans (upper two panels of Figure 4). For the oceanic processes,

wind forcing associated with the Walker circulation modulates the pycnocline depth in the northwestern tropical Pacific, which transmits to the southeast Indian Ocean. Such modulation and wave transmission result in anticorrelated variations in the zonal pressure gradients that drive the equatorward pycnocline flow in the Pacific and Indian oceans, as depicted by the opposite signs of west-east SSH differences between

the Pacific and Indian oceans (lower two panels of Figure 4). Thus, they play opposite roles in regulating tropical heat content. The change of sign in decadal tendency around the year 2000 as seen from Figure 4 is not confined to the tropics, but spans much of the Indo-Pacific domain from the Alaska gyre to the Southern Ocean (Lee and McPhaden, 2008), although the latter is also affected by changes associated

with SAM. Satellite observations also suggest a strengthening (weakening) of the Indonesian throughflow in the 1990s (2000s), which is consistent with the estimated transport of the Indonesian throughflow by existing global ocean reanalysis products (Lee et al., 2010).

In summary, satellite observations of ocean surface wind stress and SSH anomalies have revealed important zonal structure and inter-basin linkages of the Pacific and Indian ocean MOCs, and advanced our understanding of the roles of different elements of these MOCs in controlling tropical upper-ocean heat content. The decadal phase change around the year 2000 occurred when the Southern Oscillation Index reached its most positive value and the PDO index reached its most negative value in the past three decades (Lee et al., 2010). Whether the observed atmospheric and oceanic decadal changes are due to PDO or associated with decadal variation of ENSO requires further investigation.

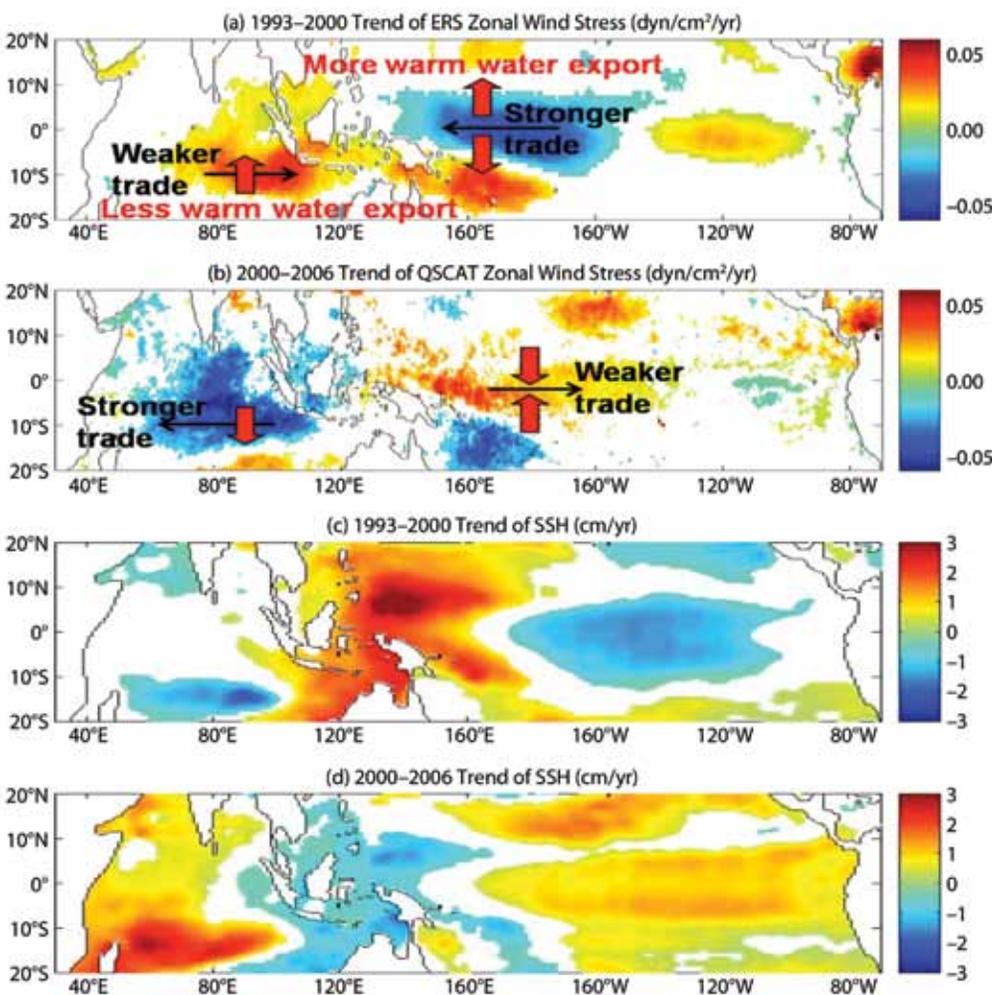


Figure 4. Decadal changes in Indo-Pacific shallow meridional overturning circulations (MOCs) inferred from scatterometer and altimeter data. Tropical trade winds (a and b) in the Pacific and Indian oceans show opposite trends before and after 2000 and anticorrelated changes in the Pacific and Indian oceans, reflecting the changes in the upper branches of MOCs. Similar features (opposite trends) are found in the sea surface height (SSH; c and d) difference between the west and east coasts, reflecting changes in a zonal pressure gradient that drives the lower branches of the MOCs. Adapted from Lee and McPhaden (2008)

FUTURE PROSPECTS AND OBSERVATIONAL REQUIREMENTS

Future Prospects

As illustrated earlier, satellite observations over the past couple of decades have allowed the oceanographic community to push the frontier of research on decadal variability. However, our knowledge about decadal variations in the ocean and their relationships with various climate variability modes are still very limited. Satellite observations have barely captured two decadal variability realizations. The signals that we observed are significantly influenced by interannual as well as decadal (and longer) variability. Therefore, many decades of observations are needed to average out the interannual signals. Sustained satellite observations in the coming decades are critical to improving the description of decadal-variability structure because the extended observations allow us to better filter out higher-frequency (e.g., interannual) variations and to identify longer-period variations.

Improved knowledge of decadal-variability structure will lead to a better understanding of the physics of ocean circulation changes and their relationships with climate variability, such as PDO, Atlantic Multidecadal Oscillation, ENSO, IOZDM, NAO, and SAM. In the tropics, interannual variability (e.g., ENSO) is dependent on the background state, which is modulated by decadal and multidecadal variability. Therefore, a better understanding of decadal and multidecadal variability will improve our knowledge of higher-frequency variability of climate modes such as ENSO and IOZDM. Extending satellite observations into the coming

decades will put us in a much better position to distinguish the effects of decadal and multidecadal variability and the impacts of anthropogenic changes.

Measurements of additional variables (e.g., sea surface salinity) open a new frontier of ocean circulation research. For example, space-borne observations of sea surface salinity will help improve the estimation of surface density and

study of decadal and longer variability and secular changes. The consistency of measurements for an ECV by different satellite missions is important to the development of a climate data record (i.e., a consistent, long data record that can be used to study climate signals). The accuracy of the satellite measurements and the biases between measurements from different satellite missions must

“...THE ACCURACY OF FUTURE MEASUREMENTS AND THE CONSISTENCY BETWEEN TWO MISSIONS MUST BE BETTER THAN THOSE FOR THE CURRENT GENERATIONS OF SATELLITES.”

thus water-mass formation, which will enhance our understanding of ocean circulation patterns such as AMOC. Increasing resolution of satellite measurements (e.g., those from high-resolution altimeters) will facilitate the study of eddy-mean flow interaction and the effects of mesoscale and submesoscale features on climate variability.

Observational Requirements

As discussed above, sustained satellite observations are expected to have a large impact on our knowledge of decadal to multidecadal variability and climate change. The most critical requirements with regard to this prospect are the continuity, consistency, and accuracy of the measurements of essential climate variables (ECVs) of the ocean from consecutive satellite missions. The continuity of satellite measurements of a particular ECV ensures the extension of the data record that is essential to the

be smaller than the magnitudes of the decadal and climate change signals that are being studied.

The requirements for ocean ECVs should include those associated with ocean surface vector wind, which is a critical ocean forcing. Ocean surface wind is often listed under atmospheric ECVs, with the corresponding observational requirement specified from the meteorological perspective. However, the ocean is much more sensitive to ocean surface wind than the atmosphere. Therefore, the accuracy requirement for ocean surface vector wind to the ocean community is more stringent than that for monitoring atmospheric variability.

Observational requirements depend on the time scales and phenomena of interest. For example, the consistency and accuracy requirements for studying PDO may be different from those associated with Atlantic Multidecadal Oscillation because the magnitudes of

a particular ECV associated with the two phenomena could be different. The same is true for decadal variability versus anthropogenic change. It is not the purpose of this paper to quantify the various requirements for different ECVs. However, we describe two strategies that can help define observational requirements for a particular time scale and phenomenon. Final observational requirements for the satellite missions can be synthesized from these estimates for different time scales and phenomena.

The first strategy is that the accuracy of future measurements and the consistency between two missions must be better than those for the current generations of satellites. For example, the differences between wind measurements from the C-band ERS scatterometer (primarily in the 1990s) and those from the Ku-band QuikSCAT (primarily in the 2000s) have limited our ability to study multidecadal variability. Future wind measurements need to exhibit accuracy and consistency better than those associated with the scatterometers of the past two decades. A dual-frequency (C- and Ku-band) scatterometer offers an excellent prospect in that regard. The second strategy is to derive observational requirements based on the magnitude of variability represented by atmosphere or ocean reanalysis products and based on the discrepancy among different reanalysis products. Future observational accuracy needs to be smaller than the magnitude of variability represented by the reanalysis products and smaller than the discrepancy among different products. This would allow us to assess the fidelity of the reanalysis products and to effectively constrain the reanalysis models.

CONCLUDING REMARKS

With their near uniform spatio-temporal sampling and (often) global coverage, satellite observations in the past few decades have advanced our knowledge of ocean circulation and its relationship with various modes of climate variability, including those on decadal time scales. Many challenges remain. Satellite observations in the coming decades will push the frontier of the research further by enabling the development of climate data records for different essential climate variables related to the ocean. Sustained and consistent measurements from satellite observations are indispensable to the monitoring and estimation of changes in ocean circulation and related property transports, to further understanding of the underlying physics of decadal changes in ocean circulation, to evaluating their relationships with decadal climate variability, and to distinguishing the effects of natural climate variability and anthropogenic changes.

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