Water and Ocean Wind Sensor (WOWS)
(Response to NRC Decadal Study RFI)

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Summary

We propose a single instrument, WOWS, that combines active and passive microwave concepts and provides co-incident and improved measurements of many key oceanic, atmospheric, terrestrial and cryospheric parameters, now being measured and will be measured by separate on-going and planned space missions. By sharing a 6-m rotating parabolic deployable mesh antenna for active and passive microwave channels from 1.26 to 37 GHz, made feasible by recent advances in antenna technology, we will enhance the spatial resolutions of many parameters and provide the coincident measurements needed to optimize the retrieval of geophysical parameters, and to characterize the multi-scale and non-linear interaction of the turbulent atmosphere and ocean.

WOWS will be the follow-on sensor for both the Advanced Microwave Scanning Radiometer (AMSR)-E on Aqua and SeaWinds on QuikSCAT, will complement Aquarius and Hydros, and inherit their technological maturity. It will continue the contiguous wide-swath measurement of ocean surface vector wind (OSVW) with the best coverage and will provided the new capability of greatly increasing spatial resolution, improving retrieval under rainy condition, and mitigating wind directional ambiguity. The coincident measurements will provide comprehensive characterization of all the essential terms in hydrologic balance over oceans and the oceanic influence of the cryospheric and terrestrial hydrologic cycles. It will enhance the characterization, understanding, and prediction of persistent small-scale ocean-atmosphere coupling, tropical cyclones, and coastal processes.

WOWS, will continue SeaWinds' long history of operational applications in global and regional marine weather prediction. It has strong potential of being part of, and cost-sharing with, the Global Change Observation Mission (GCOM)-W, which is a series of space missions planned by Japan Aerospace Exploration Agency (JAXA), and as part of the constellation of the Global Precipitation Mission (GPM). It will extend the consistent long-term monitoring to satisfy the policy-relevant objective of climate and environmental changes, yet developing new and enabling technology to sustain lives of Earth.

1 Introduction

As eloquently expounded in many National Aeronautics and Space Administration (NASA) and international documents in the past two decades, the continuous, consistent, high quality, and long-term measurements of a number of parameters, including OSVW, sea surface temperature (SST), precipitation (P), and many others, are critical to characterize, understand, and predict the changes of the Earth System. In the past few years, however, NASA has made strong effort in bridging research to operation space missions in order to free NASA's resource from the support of long-term monitoring to development of new technology. The development of a coherent application theme that has strong national policy implication and can catch the attention of the U.S. public, from a wide variety of new technology, is difficult. Furthermore, if NOAA's (National Oceanic and Atmospheric Administration) definition of operational application remains to be confined to the traditional weather prediction, the bridge is not leading to any relevant destination. A new paradigm of preserving and extending time series of the critical parameters, without sacrificing their research quality, while infusing new technology for improved and expanded applications may achieved both the goals of encouraging new and enabling technology while keeping the coherent policy relevant objective of long-term climate and environment changes. In this spirit, WOWS is being proposed

WOWS provides an evolution path for the combination of many important active/passive microwave instruments. From WOWS observations, the major components of water cycle, including precipitable water (W), the moisture transport integrated over the depth of the atmosphere (Θ), surface evaporation (E), P, SST, and sea surface salinity (SSS) can be estimated at the same time and location, under clear and cloudy sky. The Θ derived will reveal oceanic influence on terrestrial and cryospheric hydrologic balances. Thus, WOWS is relevant to the *Panel on Water Resources and the Global Hydrologic Cycle*. The water cycle is closely linked to the energy and carbon cycles, and OSVW drives ocean circulation to redistribute heat and carbon. WOWS measures climate response and impact variables, provides estimate of climate forcing and feedback, and the extension of the long time series started with SeaWinds and AMSR will make attribution to climate change on multiple time scales, from synoptic to decadal. Thus it is relevant to the *Panel on Climate Variability and Change*, SeaWinds data have been routinely assimilated in operational numerical weather prediction centers and incorporated in the analysis marine weather warning and forecast centers. They are also used in many weather related research. Thus WOWS is relevant to the *Panel on Weather*. The applications of WOWS are interdisciplinary, in both research and operation, affects weather hazards and coastal environment, have strong economic, ecological, and security impact. Thus, it is also relevant to the *Panel of Earth Science Applications and Societal needs.*

The instrument concept, and the unique capabilities of measuring the basic parameters: OSVW, SST, SSS, hydrologic parameters over ocean, cryosphere and land, are described in Section 2. The value of WOWS is more than the sum of these parameters. Examples of synergistic application of these parameters in interdisciplinary scientific studies are given in Section 3. The derivation of secondary parameters, such as, surface freshwater flux (E-P) and the divergence of Θ, to close the hydrologic balance over the ocean, is described in Section 3.1, with an example of revealing ocean's influence on cryospheric and terrestrial hydrologic changes. The potential impact of WOWS on ocean-atmosphere coupling is discussed in Section 3.2. The relation between WOWS and other missions is discussed in Section 4, and cost sharing is outlined in Section 5.

2 The Instrument Concept

This instrument will combine the active and passive microwave measurements, now being made by the QuikSCAT/SeaWinds scatterometer, the Special Sensor Microwave/Imager (SSM/I), the Tropical Rain Measuring Mission Microwave Imager (TMI), and AMSR, and will be made by Hydros and Aquarius. WOWS will use a 6-m rotating parabolic deployable mesh antenna shared by active and passive microwave channels from 1.26 to 37 GHz. This antenna technology is being implemented for the Hydros mission for global soil moisture and freeze/thaw state measurements. The frequency range allows the exploration of a wide-range of geophysical variables (Table 1).

The large antenna will significantly enhance the spatial resolution over current systems. It will provide resolution three times better than the AMSR (2 m antenna), enabling the measurements of cloud, water vapor and rain over ocean to about 6 km resolution. The large antenna will also enable the range and azimuth compression capabilities for the Ku-band radar channels to achieve super-high resolution (1 km) for OSVW needed for coastal processes and extreme weather events.

Basic parameters that can be retrieved from active and passive microwave sensors are discussed by Ebuchi and Liu [2005], and their expected improvement in Section 2.1 to 2.5.
Table 1. Mission Concept Observables for ocean, atmosphere and land surfaces.

Parameter	Accuracy	Swath	Resolution
Ocean Wind Speed/Direction	1 m/s, 20 deg	1600	1 km (high resolution mode), 5 km (Low resolution mode)
SST	0.5 deg C	1600	15 km
SSS	0.2 psu, weekly	1000	45 km
Sea Ice Edge and Concentration	10%	1600	6 km
Cloud Water over Ocean	0.1 mm	1600	6 km
Water vapor content over ocean	2 mm	1600	6 km
Rain Rate	5 mm/hr	1600	6 km
Soil moisture	0.04 g/cm^3	1000	2 km (active)/45km(passive)
Snow water equivalent	3 cm	1600	100 m (active) and 5 km (passive)

Table 2. Conceptual Mission and Sensor Parameters

WOWS - Integrated Ocean/Atmosphere/Land Observation Satellite					
Measurement	Soil moisture, SSS	SST	Rain/Wind	Wind/Sea ice/Snow	Cloud/Water Vapor/Rain/Sea ice/Snow
Current or planned measurement systems	Hydros, Aquarius	AMSR-E	AMSR-E	QuikSCAT/ASCAT	AMSR-E
Orbit	670 Km altitude, Sun-synchronous				
Frequency Band	L-band	C-band	X-band	Ku-band/C-band	K/Ka-band
	1.26 GHz/1.41 GHz	6.8 GHz	10.7 GHz	13.4 GHz/5.3 GHz	18GHz, 23, 37 GHz
Incidence Angle	40 degrees	55 degrees	55 degrees	55 degrees	55 degrees
Antenna	6-m parabolic reflector with multiple conical feeds				
Antenna spinning rate	20 RPM				
Spatial resolution	45 km	15 km	6 km	1km (SAR mode); 5 km	6km
Sensor	Radar, Radiometer	Radiometer	Radiometer	Radar	Radiometer
Polarization	Polarimetric	V, H	Polarimetric	Polarimetric	Polarimetric

2.1 Ocean Surface Vector Winds

QuikSCAT/SeaWinds scatterometer has been providing broad-swath wind vectors over global oceans, with best accuracy, highest resolution, the greatest coverage, since 1999. The 1600 km contiguous swath of the pencil-beam conically scanning 1-m antennas, provide better coverage (92% daily) than the fan-beam antennas of NASA Scatterometer (NSCAT) and the future Advanced Scatterometer (ASCAT), which have nadir data gaps where small weather systems may fall through. ASCAT will be launched on the European operational satellite in 2006. WOWS will inherit the QuikSCAT design and capability, and will not degrade the quality of OSVW (Section 4), but will have the following improvements.

2.1.1 Increase in Spatial Resolution
The QuikSCAT spatial resolution is limited by the antenna size. The QuikSCAT antenna has about 1 m diameter, providing 25-km spatial resolution. The range compression function has been built in the QuikSCAT system to sharpen the range resolution to about 5 km, but the azimuth resolution remains at about 20 Km. The use of 6-m antenna will enable the azimuth compression capabilities for the Ku-band radar channels to achieve resolution of about 1km in azimuth. The super high resolution (about 1 km) imaging capability will be critical for coastal regions and extreme weather events (see Section 3.3).

2.1.3 Improve Wind Retrieval in Rain
There are clear indications that rain affects wind retrieval, because of scattering by raindrops in the atmosphere and disturbing the ocean surface by falling rain. It is clear that the ability of wind retrieval by a scatterometer would be enhanced by coincident measurement of rain and hydrologic parameters in the atmosphere by microwave radiometer. Unfortunately, the abbreviated Advanced Earth Observing Satellite (ADEOS)-II mission did not provide a sufficiently long data set or close enough collocation for improved understanding to mitigate rain interference in wind retrieval. Historically, the European Space Agency (ESA) used the C-band (5 GHz), but NASA prefers the Ku-band (14 GHz). The Ku-band frequency is more sensitive to wind variation at low winds but is more subjective to atmospheric effects and rain contamination. The WOWS antenna technology allows the inclusion of both C- and Ku-band radar channels. The multi-frequency and combined active and passive approach will provide an optimal way to improve wind retrieval under rainy conditions.

2.1.3 Mitigate Directional Ambiguity
Polarimetric radiometry is a relatively new technique currently being developed and tested on Navy's WindSAT, for ultimate operational use to measure ocean vector wind on the National Polar Orbiting Environmental Satellite System (NPOESS). Both the scatterometer and the radiometer have ambiguity in wind direction retrievals. For a conical-scanning scatterometer, like QuikSCAT, the ambiguity is reduced by azimuth diversity, and the error in wind direction is particularly large in nadir and far zones of the swath because of poor azimuth diversity. For a polarimetric radiometer, wind direction ambiguity is reduced by frequency diversity and the error structure is spatially uniform. It has been further confirmed that the polarimetric information in active and passive microwave signals complement the symmetry properties of traditional dual-polarized microwave observations. WOWS takes the advantage of complementary characteristics; the active measurement is a cosine function while the polarimetric passive measurement is a sine function of wind direction, in their respective geophysical model functions, to provide the optimal way of mitigation of wind directional ambiguities.

2.2 Hydrologic Parameters and Sea Surface Temperature

Besides wind speed, the primary functions of microwave radiometer, such as SSM/I, TMI, and AMSR are the measurements of integrated water vapor, cloud liquid water, and rain over oceans. The observables require the 18 and 37 GHz radiometers with resolution, defined by the antenna size. Increasing the antenna size to 6 m diameter allows the resolution improvement to about 6 km at 18 GHz. TMI and AMSR include low frequency channels that are sensitive to SST. The capability of measuring SST under cloud cover has open up important applications despite the low resolution compared with traditional measurement using infrared/visible channels. The high resolution of WOWS will mitigate this deficiency.

2.3 Cryospheric Parameters

The most successful tool in studying sea ice variability is the spaceborne microwave radiometers. Data sets based on these sensors have been developed and span three decades. While the microwave radiometer provides the best measure of the global sea ice cover (extent and concentration), the scatterometer has been shown to be more useful for distinguishing between seasonal (first-year) and perennial (multiyear) ice types). A series of studies using NSCAT data from ADEOS and QuikSCAT data show that scatterometers and microwave radiometer provide excellent mapping of sea ice drift. There has been strong attempt to monitor polar mass balance using a combination of passive and active microwave sensors New techniques have been developed using SeaWinds/QuikSCAT and satellite microwave radiometer data to estimate the onset of melt and the rate of sea ice decay A comparison of AMSR-E snow depth measurements on sea ice with surface-based measurements seems to indicate a dependency of the snow depth retrieval on surface roughness something that a scatterometer can be used to measure and thus correct. The synergism of using spatially and temporally coincident passive and active microwave measurements will allow us to more effectively measure polar sea ice and mass balance.

2.4 Terrestrial parameters

Spaceborne microwave radiometers have also been used to measure snow cover and snow water equivalent (SWE). But, the onset of snowmelt has been detected effectively using QuikSCAT data. Passive microwave sensors are not capable of directly detecting wet snow. Thus, synergistic application of active and passive microwave measurements are important to quantity accumulation of snow and the identification and monitoring of snowmelt.

Soil moisture modifies the global water cycle by controlling the fluxes of water and energy at the land-atmosphere boundary. The Hydros mission will use a 6 m lightweight deployable rotating reflector, measuring at L-band, to provide a radiometer resolution of 40 km and a radar resolution of less than 1-3 km using a synthetic aperture technique. WOWS will provide comparable measurements and is strongly complementary to Hydros.

2.5 Ocean Surface Salinity

WOWS also provides an opportunity to establish a decadal time series of SSS measurements following the Aquarius mission, which is to be launched in 2009. Aquarius measures at the same frequency band as Hydros, and has an accuracy specification of 0.2 PSU (Practical Salinity Unit or parts per thousand) in monthly averages at 100 km resolution. Aquarius employs a push-broom antenna with three feedhorns illuminating a 2.5-m offset parabolic reflector to obtain a swath width of 300 km. The L-band radiometer function provides the primary information for SSS, while the companion radar channel will provide direct information for correcting the effects of surface roughness on ocean brightness temperatures. Improving the swath coverage will reduce the aliasing error. The integrated 6-m rotating antenna concept will achieve a significantly broader swath than the Aquarius push-broom design. Coincident and accurate measuring of SST will also improve the retrieval of SSS.

3 Scientific Synergism

There are science synergism among active and passive microwave sensors as reported by Ebuchi and Liu [2005]. Two areas of interdisciplinary research will be open up by WOWS and are described as examples.

3.1 Hydrologic Cycle over Ocean

The Water-Energy Cycle has been one of the scientific focuses of NASA. It is one of the scientific priorities of the U.S. Climate Change Science Program (CCSP) and a main component of the international

Global Energy and Water Experiment (GEWEX), Climate Variability and Predictability (CLIVAR) and Climate and the Cryosphere (CliC) research programs. The natural law on the conservation of mass governs the hydrologic balance in the atmosphere. The temporal change in W and $\nabla\cdot\Theta$ has to balance the fresh water flux at the surface. The fresh water flux is the difference between E and P.

The temporal change of water storage can only be transient, and, when averaged over time, the balance is between $\nabla\cdot\Theta$ and E-P. Spacebased microwave radiometers, such as AMSR, have provided estimation of P over oceans for many years. Liu and Niiler [1984] pioneered a method for estimation of E using spacebased measurements of SST, wind speed, and W. Subsequent improvements were reviewed by Liu and Katsaros [2001], and application in study ocean response to thermal forcing is demonstrated by Liu et al. [1994]. The suggestion by Liu [1990] to retrieve E directly from the brightness temperature of the new microwave radiometers, such as TMI and AMSR, with low frequency channel sensitive to SST variation has been implemented. The method to estimate Θ by relating an equivalent wind vector, which is the depth averaged velocity weighted by humidity, to surface wind velocity measured by scatterometer was established and validated by Liu and Tang [2005]. The three terms, E, P, and Θ were estimated independently, using QuikSCAT and TMI, by Xie and Liu [2004]. The similar geographical distributions of $\nabla\cdot\Theta$ and E-P as shown in the Figure 1, is one of the best validation of the estimation techniques. Xie and Liu [2005] also show that $\nabla\cdot\Theta$ and E-P agree from intraseasonal to interannual time scales and both terms show strong lag coherence with SSS at selected tropical locations where long time series of in situ measurements of salinity are available [Fig. 2]. Unfortunately, the poor sampling of in situ salinity measurements allows only comparison of low frequency variation. WOWS will measures high frequency variability of SSS coincident with surface hydrologic forcing.

The estimation of high resolution Θ using WOWS will enable the study of ocean influence on terrestrial and cryosphere hydrologic changes, as demonstrated by the monsoon study of Liu and Tang [2004]. An example of such relation in the high-latitudes by Liu et al. [2005] is presented in Fig. 3. The differences between P and evaporation (transpiration) over North America and Eurasia, north of 50°N, derived from both in situ observations and operational numerical weather prediction products were made available through ArcticRIMS (Regional Integrated Hydrological Monitoring System for the Pan-Arctic Land Mass). The time series of interannual anomalies P-E integrated over N. America (red) is almost opposite in phase with the time series integrated over Eurasia (black) in Fig. 3a. The difference between the anomaly time series for the two continents has significant correlation coefficient with the time series of zonal component of Θ over major areas of the N. Atlantic, as shown in Fig. 3b. The opposite phases of the hydrologic balances over the arctic regions of the two

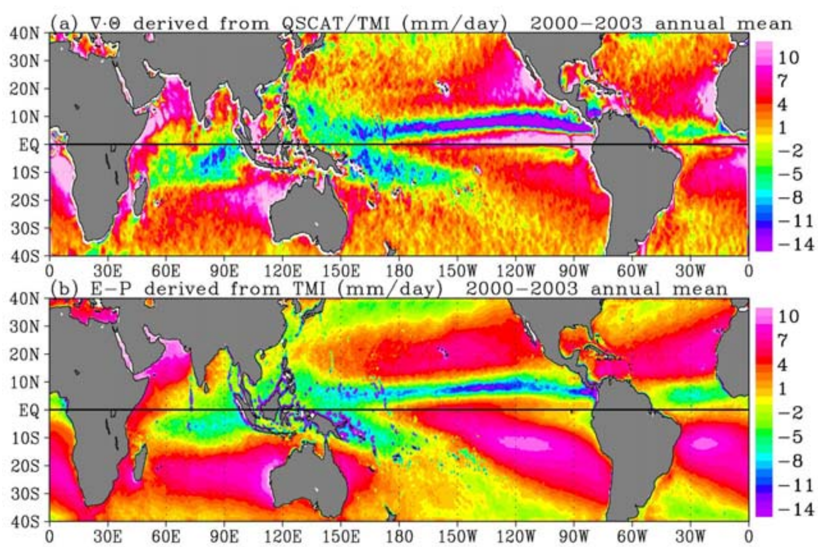


Fig. 1 (a) Annual mean (2000-2003) spacebased observation of divergence of moisture transport - $\nabla\cdot\Theta$, and (b) evaporation (E) - precipitation (P), derived from QuikSCAT and TMI (from Xie and Liu, 2005). The similar spatial patterns show the near closure of atmosphere hydrologic balance and indirectly validate the estimation of the two parameters from spacebased measurements.

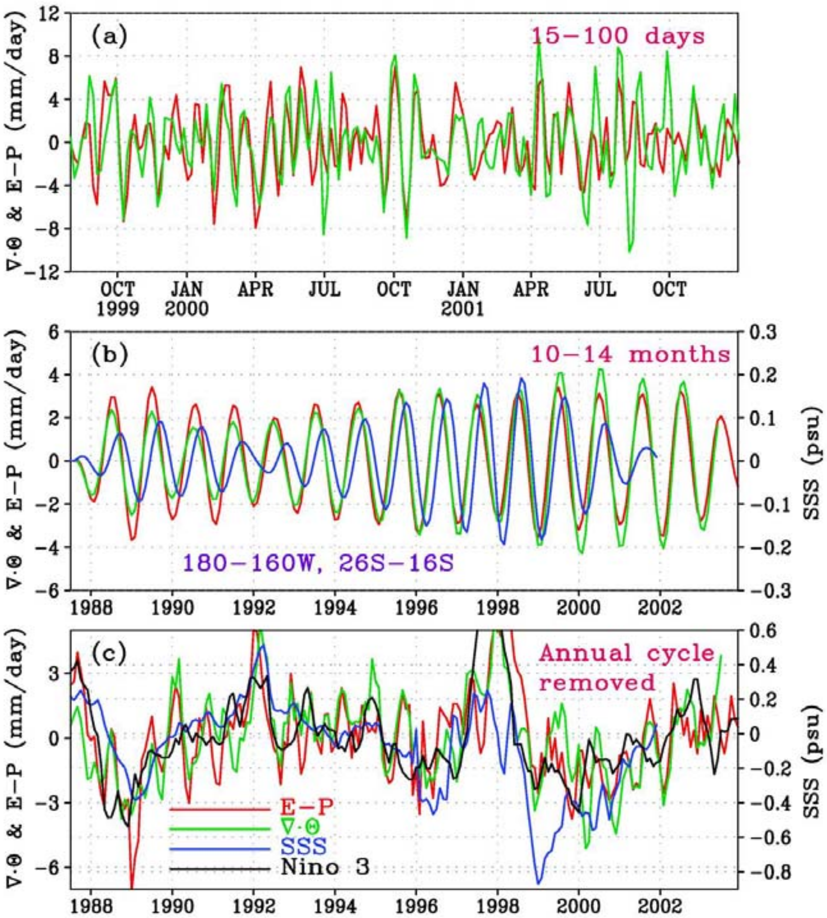


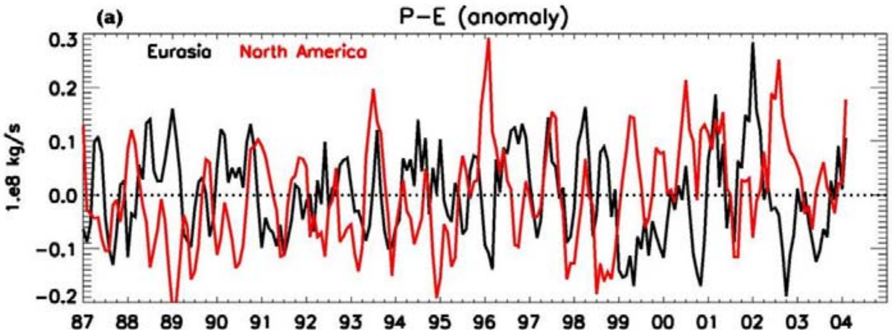
Fig. 2 Time series of ∇·Θ and E-P over south Pacific convergence zone (SPCZ) between 180°-160°W and 16°S-26°S for (a) intraseasonal variation, (b) annual cycle, and (c) interannual anomalies. SSS and Nino3 index are superimposed. The lag correlation of the two parameters with SSS in annual cycle is consistent with expected oceanic response to surface hydrologic forcing.

continents are closely linked to Θ over the N. Atlantic. Only monthly data are used in this analysis. WOWS will provide better quantification of the land hydrologic parameters and the coincident measurements will allow analysis at higher frequencies.

3.2 Ocean-Atmosphere Interaction

Wind stress is the single largest source of momentum and energy to the upper ocean. Two-dimensional wind vector field is needed to compute the divergence and curl that control the vertical mixing that brings short-term momentum and heat trapped in the surface mixed layer into the deep ocean where they are stored over time, and brings nutrients and carbon stored in the deep ocean to the surface where there is sufficient light for photosynthesis. The stored heat and carbon in the ocean are distributed by horizontal currents, driven in part by winds. QuikSCAT wind vectors with high resolution has also provided unique diagnosis information on marine meteorological processes such as cyclogenesis, and there are emerging technique to produce high resolution winds under severe conditions of marine storm that needs to be exploited in the near future. Surface wind divergence is also need to characterize the organized convective systems in the tropic serving as conduits of ocean's feedback to climate changes.

Long time-mean high-resolution ocean circulation constructed from Lagrangian drifters and spacebased altimeter data, displays persistent current systems whose spatial scales are much smaller than the scales of atmospheric circulation [Niiler et al., 2003]. However, the five years of high-resolution surface wind vectors produced by QuikSCAT have revealed persistent wind divergence and curl fields over the oceanic fronts. The persistent interaction between ocean current and wind is also found to be manifested in spacebased observations of sea surface temperature and latent heat flux. Signatures of these persistent mesoscale processes can also be observed from space in cloud liquid water and ocean color, although the coarser data resolutions do not provide sharp gradients. Nonetheless, these signatures suggest that the influence of ocean-atmosphere coupling is beyond the atmospheric boundary layer and ocean mixed layer. Fig. 4, from Liu and Xie [2005], shows the relationship between SST and wind divergence over the Agulhas Retroflection Current. An extended time series of high-resolution OSVW is critically needed.



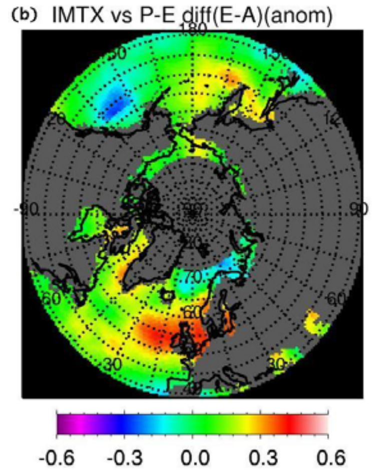


Fig. 3 (a) Time series of P-E anomalies integrated over Eurasia (black) and over North America (red) from 50°N to 80°N. (b) Correlation coefficients between the difference of the two time series (Eurasia-North America) and the zonal component of moisture transport derived from SSM/I.

Tropical cyclones (TC) at sea are hazardous to ships, and their landfall is devastating to human livelihood, because of the strong wind and heavy rain. Liu et al. [2000] demonstrated the critical need of high-resolution winds and rain to reveal the details (surface convergence and rain bands) of tropical cyclones. Yueh et al. [2001, 2003] showed that the backscatter measured by QuikSCAT over TC is sensitive to hurricane scale winds at variations rates. Lin et al. [2003 a &b] show the coincident measurements of SSTG and OSVW are necessary to study ocean’s thermal response to TC and the wind modification effect of the cold wake caused by TC. WOWS, with coincident retrieval of high resolution OSVP SST, and water parameters will greatly advance the characterization, understanding, and prediction of TC.

The high resolution measurements are also important in coastal studies. Large population lives near the coast, and costal oceans are the most productive part of global oceans. Hu and Liu [2002] demonstrated the impact of high-resolution wind in revealing the Catalina Eddy and Hu and Liu [2003] show the need of high-resolution spacebased microwave data to study the thermal and biological responses caused by the increase mixing and upwelling induced by Santa Ana wind jets. The high resolution has important in other coastal pollution and ecological applications.

4 Relation with Other Missions

Two operational sensors will provide OSVW in the future with degraded quality as compared with QuikSCAT, ASCAT, scheduled to be launched in 2006, falls back to the design of NSCAT with a large nadir gap, and it has poor spatial coverage and sampling than QuikSCAT. CMIS to be launched in 2009 will inherit the deficiencies of polarimetric radiometer - inaccuracy of wind direction at weak winds and insufficient sensities under cloudy and rainy conditions. WOWS will be the future sensor that does not degrade the present OSVW, but improves on it. It will provide cross-calibration and complementary data, not only for OSVW measurements by ASCAT and CMIS, by for SSS by Aquarius, and soil moisture by Hydros. It will become part of the constellation of GPM if launched on GCOM-W.

5 Mission and Cost-sharing

This mission will fall in the medium size category with full cost between $200-500 million. Under the auspices of the implementation plan for launching the Global Earth Observation System of Systems (GEOSS) endorsed at the third Earth Observation Summit held in Brussels in February 2005, JAXA is proposing a new mission called GCOM-W with an intended payload of a microwave scatterometer and

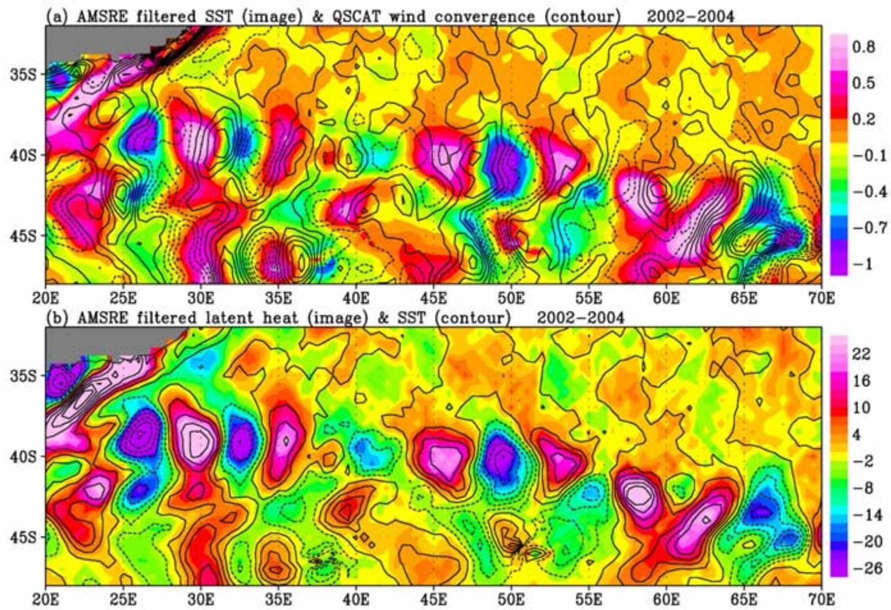


Fig. 4 (a) Filtered SST (color) and surface wind convergence (contour), (b) latent heat (color) and SST (contour), averaged from June 2002 to December 2004 derived from AMSR-E and QuikSCAT. Contour interval is 0.1 x 10^{-5} /s for wind convergence and 0.2° for SST. Data were filtered using a 10° zonal filter with a weight of sine function to remove large-scale variations.

radiometer [see Ebuchi and Liu, 2005] in its first mission planned for 2009 launch. The GCOM-W is not a single satellite mission but consists of three consecutive satellites, lasting for more than a decade. The concept of WOWS was partly encouraged by the planned mission. The first mission of GCOM-W, if launched in time, may be too early for WOWS. WOWS will still fit into the second and the third missions to satisfy both research and operational requirements. In such case, the cost sharing with the JAXA will greatly reduce the cost of U.S. contribution.

6 About the Authors

Dr. W. Timothy Liu received a Ph.D. degree in Atmospheric Sciences from the University of Washington, in 1978. He is currently a Principal Scientist at the Jet Propulsion Laboratory (JPL), California Institute of Technology. He became a Senior Research Scientist at JPL, which is equivalent to a full professor in major U.S. universities, in 1993. He has been the Leader of the Air-sea Interaction and Climate Team at JPL between 1989 and 2005. He has been the Project Scientist of a series of NASA space missions - NSCAT, QuikSCAT, and SeaWinds. Dr. Liu is a Fellow of the American Meteorological Society and his interest is in ocean-atmosphere interaction and satellite oceanography. He was selected as principle investigators or a science team member of in many Earth observing space missions, including NSCAT, Topex/Poseidon, ERS-1, TRMM, EOS, Aqua, AMSR. He has chaired and participated in many science working groups and expert panels of NASA and the World Climate Research Program. At the end of 2004, he has 121 peer-reviewed publications.

Dr. Simon H. Yueh received a Ph.D degree in Electrical Engineering from the Massachusetts Institute of Technology in 1991. He is the supervisor of radar system engineering and algorithm development group at JPL. He led the Aquarius instrument team for a successful NASA Earth System Science Pathfinder mission proposal. He has been the Principal/Co-Investigator of numerous research projects, including the polarimetric wind radiometer research; airborne scatterometer project for hurricane wind measurements; Passive/Active L-/S-band (PALS) radiometer and radar project; NASA Instrument Incubator Project for a mission concept using a large mesh-deployable antenna for soil moisture and ocean salinity sensing; the airborne polarimetric radar (POLSCAT) for ocean wind velocity measurements; the POLSCAT/Cold Land Processes Experiment in 2002-2004; and the Advanced Component Technology lightweight dual-frequency antenna feed project. He received the IEEE GRSS Transaction Prize Paper Award in 1995, JPL Lew Allen Award in 1998, IEEE IGARSS 2000 Best Paper Award, JPL Ed Stone Award in 2002, and the IEEE GRSS Transaction Prize Paper Award in 2002. He is an associate editor of Radio Science. He is on the Cold Land Process Working Group, Salinity Sea Ice Working Group, Ocean Vector Wind Science Team, and WINDSAT Science Team.

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