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Special SeaFlux Issue:
Presentations and Interviews from the 4th SeaFlux Workshop in Amsterdam

Pages 9-29

The 4th SeaFlux Workshop was held in conjunction with the Joint 2007 EUMETSAT Meteorological Satellite and 15th AMS Satellite Meteorology and Oceanography Conference, on 27 September 2007 in Amsterdam, The Netherlands. This issue of Flux News contains summaries and highlights from the talks from this Workshop.

Foreword to this issue by C. A. Clayson, the SeaFlux Project Director Page 9

Flux News intreviews Kristina Katsaros and Jörg Schulz

on the past, present and future of satellite-based measurements for air-sea fluxes

«...you need to teach young people a healthy suspicion of data, including satellite data. Your data is only as good as the calibration, sampling and processing».

Pages 5-8

«Today we have 3-4 consolidated global ocean flux data sets that have been reanalysed 2-3 times. The data sets range from pure remote sensing products to remote sensing, in situ, model data coupled products all serving different applications».

Surface Fluxes and WCRP Science

Pages 2-4

Flux News presents a concept paper by S. Gulev, C. Fairall and V. Ryabinin to provide the ground for discussion on the importance of surface fluxes in WCRP science at the forthcoming JSC-29 meeting in Bordeaux, France

The aim to better observe and predict climate poses new challenges for the air-sea flux community. The most important challenges are to minimize the uncertainties in estimates of global surface fluxes, and to improve our understanding of the global energy balance. Moreover, we have to achieve much better accuracy in the estimation of air-sea flux variability on the time scales from several years to several decades. This is equally important for surface fluxes both over the oceans and the continents.

Given the complexity of these issues and the necessity to deal with physical and biogeochemical exchanges at the same time, the WCRP now faces the need to provide more coordination in this area. The WGSF should be, therefore, transformed into a group with expertise in all these scientific areas covering different space-time scales and various sources of surface flux estimates. We now need a pan-WCRP surface flux endeavor. The end of the current term of WGSF should see the provision for an extended mandate.

Surface Fluxes and WCRP Science

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Looking back from 2008

Over the last 4 years the WCRP Working Group on Surface Fluxes (WGSF) has carried out a considerable amount of work. Good progress has been achieved in our understanding of the mechanisms forming air-sea flux variability on different temporal and spatial scales. New flux products of higher accuracy and finer resolution have been developed and can now be used for all types of climate research. WGSF by far exceeded the expectations formulated by the JSC in the ToRs by initiating systematic validation activities, building new methodologies of air-sea flux field production, developing guiding materials for climate-quality flux observations and assessing all sources of errors and uncertainties in the air-sea flux products. The mandate of WGSF also covered ocean-atmosphere biogeochemical fluxes. Cooperation of WGSF and SOLAS in this area has been very strong, and helped to bridge WCRP with IGBP. Now, when the term of WGSF is to expire, it is time to plan an extended surface flux enterprise for WCRP.

The surface flux activities of WCRP have been going on for 11 years. Between 1996 and 2001 there existed the Working Group on Air-Sea Fluxes (WGASF). WGSF took over from them in 2003 targeting the problem areas identified in the comprehensive review of flux science and practices (WGASF 2000). WGSF's progress in 2003-2007 has been associated with a number of specific accomplishments. A Guide to Making Climate Quality Meteorological and Flux Measurements at Sea by Bradley and Fairall (2006) has provided the most comprehensive compendium to observational practices and estimation of air-sea fluxes at sea. New observational programmes contributed to better parameterization of radiative fluxes (e.g. Fairall et al. 2007) as well as turbulent fluxes. The VOSClim project (Kent et al. 2007) together with the OceanSITES initiative (http://www.oceansites.org/index.html) have become the source of reference flux observations by Voluntary Observing Ships (VOS) and high quality flux data from buoys. They form firm ground for validation of all types of flux products, be they VOS-based, remotely sensed or NWP-derived. New metadata (Kent et al. 2007) along with new algorithms for corrections of marine meteorological variables and estimations of sampling errors in VOS records and fluxes (Kent and Berry 2005, Gulev et al. 2007 a,b) open a new era in the development of VOS flux products. Continuously updated ICOADS collection of marine observations (Woodruff et al. 2005) forms the basis for such products.

> BETTER CLIMATE OBSERVATION AND PREDICTION CAN ONLY BE ACHIEVED IF WE MINIMIZE THE UNCERTAINTIES OF THE GLOBAL ENERGY BALANCE AND INCREASE THE ACCURACY OF THE ESTIMATION OF VARIABILITY OF AIR-SEA FLUXES ON ALL TIME SCALES

Global satellite-derived air-sea flux products (see this issue) have now achieved the space-time resolution matching that of operational NWP flux products and cover the periods up to 2 decades. This led to the development of the global blended products based on synthesis of in situ measurements, merchant ship observations, satellite data and reanalyses (Yu and Weller 2007). As regards NWP-generated air-sea flux products, their validation against high quality in situ measurements is on the way under the revitalized SURFA project of WGSF and WGNE. The development of air-sea flux products for the forcing of ocean GCMs (see Flux News 3) considerably improved the quality of simulations of ocean general circulation in different resolutions. Furthermore, the ocean state estimation by GCMs in data assimilation mode now provides new surface net heat and freshwater flux products consistent with oceanic observations (Stammer 2007).

New observational and modeling activities in air-sea interaction at high latitudes in the presence of sea ice (see Flux News 4 articles) have improved our understanding of air-sea interaction in the Arctic and Antarctic, including impacts of air-sea fluxes variability on sea ice thickness, which itself is the measure of the air-sea flux. The progress in the WGSF-SOLAS co-operation is manifested in two major reviews (nearly completed) on gas and particle transfer by W. McGillis and G. De Leeuw. Also, over the last 4 years there were other numerous observational and modeling activities (covered in Flux News 2, 3 and 4) which established more accurate quantitative estimation of surface biogeochemical fluxes including deposition.

Surface fluxes adding value to climate observation and prediction

The aim to better observe and predict climate poses new challenges for the air-sea flux community. Firstly, we need to minimize the uncertainties of estimates of global surface fluxes, and to improve our understanding of the global energy balance. Global residual estimates of Trenberth and Fasullo (2007), Fasullo and Trenberth (2007) and Liu and Xie (2008, this issue) show a possibility of obtaining accurate estimates of air-sea energy balances on global and regional scales, including estimates of meridional transports of mass and energy in the climate system. In order to evaluate such global balance estimates we now need to deliver surface flux products adequately representing them. Secondly, we have to achieve a much better accuracy in the estimation of variability of air-sea fluxes on time scales from several years to several decades. This is especially important now when satellites have started to provide global multi-decadal homogeneous radiative flux products at weather-scale resolution (e.g. Zhang et al. 2006). The crucial role that surface fluxes play in climate variability is obvious, however the proper quantification of this role is still hampered by an insufficient accuracy of surface flux estimates. Progress in this area, if achieved, will allow to extensively analyse surface fluxes in coupled model runs including the future climate simulations. This will help to understand the role of fluxes at the air-sea interface in the climate change. In this context, the continuing co-operation with SOLAS will be very important for quantifying the ocean's role in the redistribution of the greenhouse gases, first of all carbon dioxide.

> SURFACE LAND FLUXES PLAY A CRUCIAL ROLE IN REGIONAL CLIMATE VARIABILITY. LANDFLUX AND ILEAPS PROVIDE A COMPREHENSIVE ANALYSIS OF BOTH PHYSICAL AND BIOGEOCHEMICAL SURFACE EXCHANGES OVER LAND

Surface land fluxes, although smaller in magnitude compared to air-sea fluxes (Fasullo and Trenberth 2007), exhibit much stronger spatial differentiation and may play a crucial role in regional climate variability. Although the uncertainties in the estimation and parameterization of surface fluxes over land are in many respects different from those of air-sea fluxes, they are also large. The LandFlux initiative launched recently by the GEWEX Radiation Panel in co-operation with the GEWEX Land Surface Study (GLASS) is expected to address this situation by producing a new generation global, multi-decadal surface turbulent flux data product. Importantly, LandFlux is developed in co-operation with the Integrated Land Ecosystem-Atmosphere Process Study (iLEAPS), targeting (among other issues) the mechanisms of gas fluxes over land controlled by vegetation. Similarly to WGSF and SOLAS in the area of air-sea fluxes, LandFlux and iLEAPS provide a comprehensive analysis of both physical and biogeochemical surface exchanges over land.

> SKILLS OF SEASONAL AND DECADAL PREDICTIONS CRUCIALLY DEPEND ON THE ACCURACY OF ESTIMATION AND PARAMETERIZATION OF OCEAN SIGNALS REPRESENTED BY SURFACE FLUXES

Challenges for a 2008+ WCRP Surface Flux enterprise

Given the complexity of the issues related to surface fluxes over the oceans as well as over land, and the necessity to deal with both physical and biogeochemical exchanges at the same time, the WCRP now faces the need to provide more co-ordination in this area. The Working Group on Surface Fluxes can, therefore, be transformed into a group with expertise in all these scientific areas, covering different space-time scales from micro-scale to the global scale, from seconds to decades, as well as different sources of surface flux estimates (in situ, satellites, NWP). In its new capacity WGSF shall work in a close co-operation with all WCRP core projects (GEWEX, CLIVAR, SPARC and CliC), panels (WOAP and WMP) and working groups (WGNE and WGCM). The aim of the future working group should be to continuously address the changing requirements of all WCRP research components in surface fluxes and to facilitate the generation of new flux products representing ocean-atmosphere (including sea ice) and land-atmosphere physical and biogeochemical interactions. The inclusion of land fluxes into surface flux work fits in perfectly with the goals of CLIVAR linking, in particular, ocean signals with the continental climate variability. Furthermore, the CLIVAR achievements in the evaluation of air-sea flux datasets against in situ observations (Josey and Smith 2006) should enrich the existing surface flux validation activities and initiate new ones. This multitask working group will be more than relevant to GEWEX which currently leads both SeaFlux and LandFlux activities. Finally, such a group will be of benefit to CliC which deals with fluxes associated with both marine and terrestrial cryosphere.

The WGSF in its extended format will undoubtedly contribute to the existing cross-cutting activities of WCRP. Sea level rise is largely driven by evaporation and precipitation processes. The annual change in the latent heat flux by 1 W/m^2 is equivalent to the oceanic water column of 12 mm. In terms of sea level change, this value is one order higher than the observed rate of change. At the same time, even for the state-of-the-art long-term air-sea flux estimates, this accuracy is hardly achievable. Variations of surface net heat flux during several weeks of the Indian monsoon break cycle may be as large as 100-200 W/m^2, however an accurate estimation of this signal requires much better spatial and temporal resolution of the flux fields than that we have now. The skills of the seasonal and decadal prediction crucially depend on the accuracy of estimation and parameterization of ocean signals represented by surface fluxes. Many of extreme weather and climate events are associated with intensive tropical and extra-tropical cyclones. Surface turbulent fluxes in such cyclones may locally amount to 2000-3000 W/m^2 which is an order of magnitude larger than mean monthly and seasonal values. Accurate quantitative estimation of these extreme fluxes requires the extension of the existing and the development of new parameterizations. Given the objective limitations of in situ flux measurements in severe weather environments this requires consolidated effort in laboratory modeling, surface layer theory, remote sensing and analysis of surface flux statistics. Furthermore, extreme events over the continents are often strongly localized in space and time and, therefore, their physical description and prediction requires accurate estimation of land-atmosphere fluxes with very high space-time resolution. Surface fluxes, being responsible for re-distribution of energy and gases between the components of the Earth climate system, play a crucial role in the projection of the anthropogenic climate change. The Atmospheric Chemistry & Climate initiative of WCRP does not directly deal with the Earth surface processes. However, in the future, biogeochemical exchanges and, in particular, those tackled in co-operation with SOLAS and iLEAPS, will definitely contribute to this important sector of WCRP science.

IN ORDER TO MEET THE NUMEROUS CHALLENGES IN SEA-AIR AND LAND-AIR INTERACTIONS WE NOW NEED A PAN-WCRP ENDEAVOR IN THE AREA OF SURFACE FLUXES. THE END OF THE CURRENT TERM OF THE WGSF SHOULD SEE THE PROVISION FOR AN EXTENDED MANDATE

Considering the growing role of climate science as a component of the ESSP, it is very important that WGSF continues to maintain an effective link between WCRP and IGBP. Today, WGSF and SOLAS provide an important pillar of the bridge between these two programmes. Potential collaboration with LandFlux and iLEAPS on land-atmosphere fluxes including biogeochemical exchanges can become another such pillar. As regards the WCRP involvement in regional climate change, the WGSF shall prioritize methodologies of the adaptation of global surface flux products to regional scale by refining spatial and temporal resolutions. Again, this is a challenging goal for both air-sea and land-atmosphere surface flux activities.

In order to meet these numerous challenges we now need a pan-WCRP endeavor in the area of surface fluxes. The end of the current term of the WGSF should see the provision for an extended mandate. Also, bearing in mind the current financial difficulties of WCRP, the Working Group on Surface Fluxes which has proved to be the most cost-effective activity of WCRP, will fit in perfectly with the Programme's budget.

The WGASF/WGSF achievements over the last 11 years, the involvement of all the WCRP core projects, panels and working groups, as well as well the established practices of operation and such instruments as Flux News and the Internet resources, should guarantee the usefulness and steady success of an extended WGSF.

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WE HOPE THAT THIS CONCEPT ARTICLE PROVIDES THE GROUND FOR DISCUSSING THE FUTURE CO-ORDINATION OF SURFACE FLUX WORK. WE INVITE COMMENTS FROM THE SURFACE FLUX COMMUNITY, REPRESENTATIVES OF ALL WCRP PROJECTS AND GROUPS, AND JSC MEMBERS PRIOR TO THE 29TH ANNUAL SESSION OF JSC IN BORDEAUX, FRANCE, 31 MARCH - 4 APRIL 2008.

THE INTERVIEW

At the 4th SeaFlux Workshop in Amsterdam we had a pleasure of talking to two eminent figures in the world of fluxes: **Professor Kristina Katsaros**, the former Director of the Remote Sensing section at IFREMER and the NOAA Research Laboratory in Miami, USA, and **Dr. Jörg Schulz** of the Deutscher Wetterdient (DWD) in Offenbah, Germany. We asked them to share their opinions on the past, present and future of satellite-measured air-sea fluxes.

Flux News: In the early 1990s there was a strong belief that the future of air sea fluxes was all in satellite-based measurements. Has it materialized?

Kristina Katsaros:

From listening to lectures here at the Seaflux workshop for the whole day and also at the recent sea-air interaction meeting in the United States, also sponsored by the American Meteorological Society, I think there is a fantastic opportunity to do some significant science with the satellite fluxes now. However, there is still room for improvement, especially now when we have sounders that can provide profiles in the whole atmospheric column, which, therefore, may allow calculations of sensible and latent heat fluxes to better accuracy. The evaporation rate (latent heat flux) is still a rather approximate calculation. Nor can we yet depend entirely on satellite observations. At least we must use in-situ measurements for calibration.

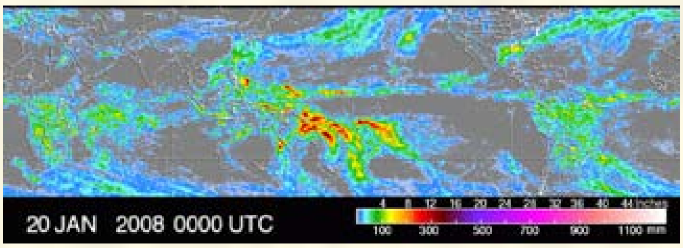
Radiative fluxes are being improved by higher spectral resolution and use of data from geostationary satellites. This allows us to measure the diurnal variations of radiative fluxes and other surface parameters at high resolution in both space and time. The future is just as promising as it looked in the past; I mean as the recent past looked about 10-15 years ago. Thanks to the wide-coverage by satellite data we can look at more and more interesting processes, such as the variability of fluxes in the areas surrounding eddies in the ocean and near coastal fronts. We can now look at smaller scales and at different kinds of processes. There is no risk that it becomes uninteresting.

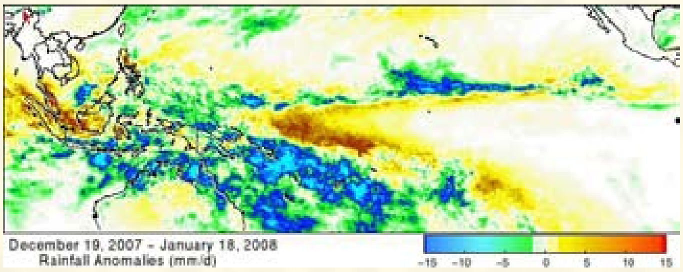
I think that there are still tremendous opportunities to discover and develop improvements to satellite-based estimates of global air-sea fluxes.

Jörg Schulz:

Definitely yes! During the early 90s a few research groups tried to derive parameters of the bulk formulae employing passive and active microwave and infrared measurements. The resulting algorithms were applied to only a few data, say several months. I remember me travelling to the University of Colorado to Bill Emery to copy SSM/I data to bring them to Germany where my disk space was only large enough to hold one month of SSM/I data. I'm still grateful that this was possible.

Today we have 3-4 consolidated global ocean flux data sets that have been reanalysed two or three times. The data sets range from pure remote sensing products to remote sensing, in-situ, model data coupled products all serving different applications. Ocean modellers, that are still sceptical about the quality, try to assess the value of these data sets which is a great help for further development. Although we have discussed here at the SeaFlux workshop that the data sets show some unrealistic trends they have already been used in a lot of studies of climate phenomena as Northern Atlantic Oscillation or Indian Monsoon. Also the combined use with precipitation and water vapour data sets allows for computation of large scale atmospheric water vapour fluxes which may have value for assessing the quality of Global Circulation Models of the atmosphere.





Some recent TRMM products (Source: NASA Goddard Space Flight Center, http://trmm.gsfc.nasa.gov/).

Flux News: Which satellite mission(s), starting from 1980, do you consider the most successful?

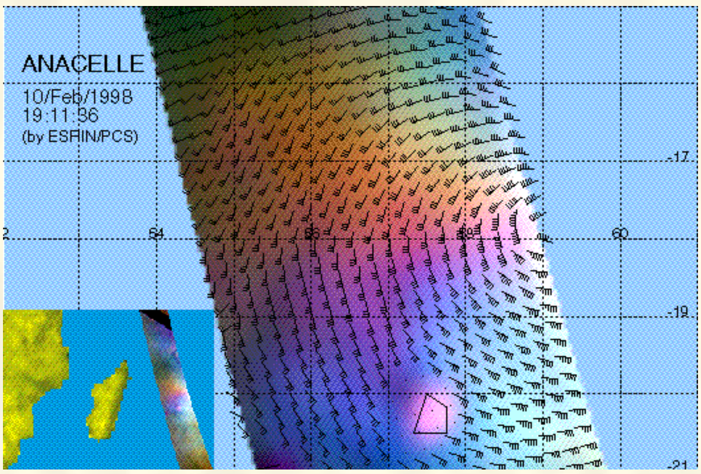
K. Katsaros: In the late 80s the first Special Sensor Microwave/Imager, the first SSM/I, was launched, and there was a series of them. I think we are now at number 16 and more are on line. I do not think we realized the full value in the beginning, because we had had the Scanning Multi-channel Microwave Radiometer (SMMR) for a long time. The SSM/I is similar to SMMR, but it has the 85Ghz channel, valuable for looking at ice particles in clouds, and by now it has provided this remarkable long-term continuing dataset with well chosen frequency bands. The choices had been developed over a 20 year period. The long and consistent record has proven very valuable for climate analyses. Even though we still hear, also at this meeting, about some bias adjustments or trends that may not be realistic, the SSM/I has provided a tremendous dataset.

And then, finally, beginning in 1992, we got European Remote Sensing spacecrafts ERS 1 and 2 with scatterometers on board, which measure surface wind speed and direction (or wind stress over the ocean). We have had NSCAT on ADEOS I and Seawinds on ADEOS II which are NASA scatterrometers, but unfortunately they did not last very long. After the loss of ADEOS II, the mission was replaced by QuikSCAT (in 1999). Its scatterometer, Seawinds, has a wide, continuous swath of 1,500 km and it has operated well since launch--for more than 8 years. Seawinds is a very successful instrument, which researchers and marine forecasters are still learning to use. The Europeans have another scatterometer, ASCAT, on the METOP satellite, which has just been commissioned. It has a C-band radar like the ERS 1 and 2.

There is a U.S. proposal to have a combined Ku-band and C-band scatterometer. This is a development that could give a whole new approach. The special advantage is that we might be able to correct for the rain interference more effectively because of the two wavelengths. Scatterometry is important for winds, which represent the dominant variable when estimating the turbulent fluxes. But.... if you look at the maps of fluxes derived from satellites, you will find that one SSM/I and one scatterometer will not give you complete air-sea flux estimations over the globe and not very frequently. We need multiple satellites for proper sampling over the global ocean.

To summarize: microwave radiometers, scatterometers, and the higher resolution geostationary satellites for the visible and infrared – all these are going forward to better resolutions, better accuracies and better calibrations.

When answering questions like the one you just posed, I really come to appreciate what has been done over time. People are now crying for scatterometers to be launched, the new and improved ones. Others want just a replacement for QuikSCAT, because they have become dependent on it for forecasting. Microwave radiometers are taken for granted, just as the infrared polar orbiting sensors have been for a long time.



Normalized radar backscattering and wind field from the Anacelle cyclone (in the Indian Ocean, close to Madagascar) as seen by the ERS-2 Scatterometer. (Source: ESA, http://earth.esa.int/pcs/ers/cyclones/introduction/introduction-1.gif)

J. Schulz: For me it is clearly the SSM/I instrument series that established one of the most stable temporal records of satellite data of ~20 years. The passive microwave imagers have an on-board calibration the radiometric quality was good from the beginning. Because the data were available and can be handled relatively easy we were able to learn a lot from it. When my colleagues and I put together the first version of the HOAPS data set at the University of Hamburg in the late 90s, we first came across that different instruments and orbit characteristics of the satellite platforms almost destroyed our temporal records. But this has initiated a lot of good work that resulted in effective corrections leading to very homogeneous radiance records today. There is still a lot to do in the field of inter-calibration to get the trends right, but compared to the beginning of the 90s the data sets have greatly been improved.

Another instrument that comes to my mind is the TRMM Microwave Imager (TMI). This instrument has a 10 GHz channel that restarts activities to derive sea surface temperature from both infrared and microwave measurements in the late 90s. Additionally, TRMM provided the perfect link to precipitation measurements.

All the lessons learnt with these and other instruments led also to the GCOS (Global Climate Observing System) climate monitoring principles that are more and more recognized by the space agencies during the development of satellite programs. The principles, if followed, lead to temporal records of satellite data that can be stitched together well because there is among other things overlap between missions carrying the same kind of instrument. Another very important principle is that the relevant meta data of the instruments are kept to make a successful reanalysis of the data possible.

Flux News: Satellite climatology/marine meteorology in general and the remote sensing of air-sea interaction in particular require some special skills from young researchers, especially the knowledge of theoretical meteorology of satellite technologies. Should any special courses be launched at universities?

K. Katsaros: I am impressed by the young people, and they have good teachers, so they are learning what they need, obviously, but was it easy for them to get up–to–speed? That is the real question.

We have had special courses in remote sensing for students where I have been in France (Brest, Université de Bretagne Occidentale and Université Paris 6) and at the University of Washington in the USA. In fact, we have not had very many formal and complete courses – no one teacher can usually manage that. At all these places we had a team to teach remote sensing to graduate students. By that time they had already finished their basic course work in atmospheric dynamics and atmospheric physics and/or oceanography. I do believe we must teach remote sensing, but this is such a broad field! How can we do it well? Maybe some short training courses for scatterometry and microwave radiometry would be most effective besides the basic classes about instrumental techniques, satellite orbits and such. Maybe graduates have to go to places like the National Center for Atmospheric Research in the USA, or one of the European Geoscience Institutions and get an intense course during which they would be introduced by oceanographers and meteorologists to what is available among different satellite products and what is coming on line. Such centers exist also in Japan, in Indonesia, in India etc.

Or...they can go to remote sensing conferences, where regular tutorials could be offered on various aspects of remote sensing. I have participated in such short courses in the past as one of several lecturers. The PORSEC (Pan-Ocean Remote Sensing Conference) Association regularly organizes courses in remote sensing at their conferences—(see http://porsec.nwra.com/about.php). We have a conference every two years with tutorial courses in relation to those meetings. Lately we have focused on the Synthetic Aperture Radar (SAR) and ocean color algorithms — some of the recent developments in oceanographic remote sensing. That kind of thing can be done more widely. There is an offering that we heard about at this conference: training through the WMO (World Meteorological Organization). All of this training often takes place separately from formal university education, but more and more professors include the use of remote sensing in their general lectures.

One other thing I would like to say about this is that you need to teach young people a healthy suspicion of data, including satellite data. Your data is only as good as the calibration and sampling (and processing). If you have never taken measurements yourself, you will have a problem recognizing and dealing with errors or uncertainties caused by thermal drifts, calibration drifts, etc. Therefore, a little bit of suspicion is very good. I do not know if it can be taught.

SSM/I craft in space (Source: Polar Satellite Precipitation Data Center, http://gpcp-pspdc.gmu.edu/images/SSMI.pic.gif)

J. Schulz: To generate remotely sensed air-sea fluxes, assess their quality and do climate analysis with them requires education in very different fields. On one side there is the pure remote sensing part including instrument physics, radiation transfer theory and retrieval techniques. The last two are also parts of data assimilation procedures, i.e., inverse radiation transport codes are used to perform retrieval instead of statistical approaches.

On the other hand you also need a sound background in boundary layer meteorology and oceanography. Normally, young researchers are specialized in one of these fields and need to gain experience in the other fields. For instance, when a young researcher experienced in the remote sensing part starts to compare satellite-derived fluxes with climate model simulations and/or ship measurements a lot of additional knowledge is necessary to determine how such a comparison should be designed and how the results should be interpreted.

Having this in mind I do not see that the “flux” topic is really suitable for a special University course. University lecturers should try to make links to remote sensing when they give courses on air-sea interaction. However, the more experienced people still have the responsibility to pass on their knowledge about this very interesting field to the younger generation. A good way to do this might be summer schools where you can take up all the different aspects of the field. I think that the people participating in the SeaFlux workshop already represent a good mix of topics for such a summer school event.

Flux News: Satellite-based fluxes still require in-situ observations to be properly validated. What, in your view, are the major requirements for in-situ observations and do you expect them to change in 5-10 years time?

K. Katsaros: I do not know if I can look into the future, even 5 to 10 years ahead. We have been measuring the mean state variables in the atmosphere, and we have learned to worry about the interference of the ship, such as the heat island the ship makes, the reflection of the sun from a ship, and the distortion of wind flow around the ship and the whole spectrum of problems with ship data. If you put a buoy in the ocean they can lose accuracy, or have long holes in the data, because you need a ship to go out and fix the buoy's instruments far away from the coast. It is very hard to achieve a stable long-term calibrations; that is true even for the tropical Atlantic warm pool with a relatively mild climate. I think good calibrations and investments in instruments which are self-cleaning are something that we are always going to need in the area of in-situ sensors.

However, the major difficulty is to get close to the property you are trying to measure – the air-sea fluxes. People talk a lot about direct flux measurements. Sonic anemometers have been operated on ship towers or on buoys for long periods of time in recent years (giving momentum and virtual heat flux), but usually only for a few weeks or a month. Using them successfully on unattended buoys seemed for my generation almost impossible due to the motion corrections that are required. I am not well informed about how well this is being done routinely now, nor am I convinced that it is so important to measure the flux directly everywhere. We have done a lot of work in parameterizations of fluxes in terms of "bulk" surface variables. These parameterizations have been tested over and over, and the variability that still exists in the fluxes is often due some other parameter which we do not measure, such as the waves. We know that there is a shift in the momentum flux-values (the stress), whether you have swell going with or against the wind. Things like that are not often included in the bulk parameterizations, but could be. Then we also would need to measure those "other" variables, not only the wave field but also surface currents, meso-scale atmospheric structures.... And better coverage by the sampling should be provided.

Something more ideal in terms of in situ measurements may be in the offing now with the buoys in the ARGO program. There are 3,000 of them all over the global ocean. They give us the opportunity to do things we talked about at this workshop, such as calculating energy budgets for the upper ocean. You can achieve the global coverage, and even if the buoys are most of the time below the sea surface you can derive the storage of heat and the advection of heat. In other words, they might help you interpret your satellite flux estimates. Thus, planning for in-situ and satellite remote sensing measurements should be a joint effort with common objectives.

J. Schulz: This question is really hard to answer. However, as a concept I would propose to have very accurate direct air-sea flux measurements accompanied by standard atmospheric and oceanographic measurements, e.g., wave features etc. This kind of data is best used to further improve flux parameterisations and to show what errors can be expected if not the full needed information is available for the parameterisation. This would be beneficial for the development of remote sensing products as well as for the development of climate and weather prediction models.

For the validation of remote sensing flux products we really need measurements over long periods. We have seen here at the SeaFlux workshop how difficult it is to collocate ship data from field experiments with products that mostly give a temporal mean in a grid box that covers (2,500 km^2). So it might be better to compare at a reference site an even parameterized flux with the satellite-derived flux but for a decade or more. Then we are better able to diagnose if a satellite data set gives us correct answers with respect to variability and/or trends. However, this also requires that the ground-based time series are analysed very well so that we can be sure that variability and trends at such a site are real and not an artefact.

Furthermore, validation may also be extended by indirect means as the usage of satellite-derived fluxes to force ocean models which might be a better test for their quality than comparison to other data. Also the common analysis of precipitation, evaporation and water vapour in the atmosphere as mentioned before can clearly give information on the quality of the flux fields.

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THE 4TH SEAFLUX WORKSHOP

Foreword

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The SeaFlux Project is dedicated to producing climatological global data sets of air-sea fluxes of heat, moisture, and momentum from satellite-derived products under the auspices of the GEWEX Radiation Panel. The Fourth SeaFlux Workshop was recently held in conjunction with the Joint 2007 EUMETSAT Meteorological Satellite and 15th AMS Satellite Meteorology and Oceanography Conference, on the 27th of September, 2007 in Amsterdam, The Netherlands. A number of the presentations during this workshop are highlighted in this Flux News issue, and cover many of the topics that SeaFlux is dedicated to addressing.

The issues that SeaFlux is tasked with contributing include determining the highest-resolution (in time and space) air-sea turbulent flux dataset that is feasible, and analyzing the quality of the resultant turbulent flux datasets as relative to in situ and NWP products. These two topics are being addressed as part of the SeaFlux Intercomparison Project. This project uses data from in situ research-quality fluxes that have been gathered since July 1987. These in situ fluxes, the satellite-derived flux datasets that are a part of the Intercomparison Project, and many other details of the SeaFlux Project can be found at the SeaFlux website at http://www.gfdi.fsu.edu/SEAFLUX. A component of these comparisons is to make the process as transparent as possible, so that in the future new datasets can be directly compared in the same manner. In addition to the forthcoming article related to the comparisons, the website also is constantly being updated with Matlab and other routines to help researchers make their own comparisons or to determine which data sets might be best suited to their needs.

Since the production of global satellite-derived turbulent fluxes involves multiple steps, including the retrievals of near-surface and surface fields of temperature, winds, and humidity, the use of appropriate space-time gap filling, and using bulk flux parameterizations to turn the bulk input variables into turbulent fluxes, SeaFlux relies on research that focuses on the best practices related to each of these topics. It is evident from the comparison work that is currently being performed that, for instance, many of the research-quality in situ measured fluxes are undertaken as part of experiments that do not directly consider the needs for comparisons with satellite fluxes. Fluxes from a ship that may move over a one-day period through multiple satellite pixels make comparisons with daily-averaged satellite fluxes challenging, and do not allow for a definitive statement as to the absolute bias (if any) of the satellite-derived fluxes. Thus the needs of the SeaFlux community complement many of the other air-sea surface flux projects such as WGSF, and we hope to continue discussions that benefit all of us.

In addition to comparisons of currently existing data sets, and the production of the first SeaFlux datasets, other new or updated datasets are constantly being introduced. New methods in determination of the input variables for turbulent heat fluxes were discussed in talks by W. Timothy Liu, John Bates, and Darren Jackson. Kristina Katsaros and Rachel Pinker discussed issues related to radiation fluxes and a determination of the total energy budget, and Yuanchong Zhang provided insights regarding decadal variations in the global atmospheric and oceanic heat budgets. Longer-time series variability was also investigated by Abderrahim Bentamy and Axel Andersson. Some comparisons of the current data sets to in situ data sets were shown by Mark Bourassa and Brent Roberts, and Sergey Gulev provided information about issues related to comparisons of datasets from non-uniform sources (such as ships of opportunity). This issue of Flux News contains summaries and highlights from many of these talks. We hope that these selected articles will give the reader who is unfamiliar with SeaFlux an introduction to the work being undertaken by the participants of the SeaFlux Project.

Call for contributions:

Flux News 6 is currently scheduled for July 2008.
Papers on all subjects of air-sea and air-land interaction are welcome.
Please send your contributions to fluxnews@sail.msk.ru
by 15 May 2008.

Atlantic Air-Sea Fluxes from Satellites, their Variability and Analysis of Ocean Models: Background

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The motivation for forming an interdisciplinary team to assess air-sea fluxes over the tropical Atlantic ocean was to estimate all the flux components as well as possible so that the magnitude of net heating or cooling can be established. Previous studies based on data from ships and buoys, have shown that our knowledge of the tropical Atlantic ocean is not adequate. For instance, models of the thermocline generate the wrong slope of the isotherms from east to west, possibly due to limited input data. Atlantic studies have linked sea surface temperature gradients and patterns to rainfall in Brazil and the drought periods in western Africa (e.g. Foltz et al. 2003). The limited data leave many open questions. Climate and ocean studies require that all the energy flux terms in the air-sea exchange be known as accurately as possible. The objective of the team work described here is to attain improvements in flux data by using measurements from satellites that can provide good spatial coverage and work on improving temporal coverage. The test of the adequacy of our estimates will be by comparison to heat content changes observed by satellite altimeters and by running ocean models with these fluxes as forcing, in particular, the Simple Ocean Data Assimilation (SODA) model (Carton and Giesel 2006). The derived fluxes will be also compared to numerical model outputs as well as to other flux products (e.g. Grassl et al. 2000, and later reports) and in situ observations, as was done for an earlier version of our turbulent flux product (Bentamy et al. 2003).

A 15 year-long record of turbulent air-sea fluxes of latent and sensible heat (the IFREMER/CERSAT product) will be used. It is based on scatterometer wind fields and Special Sensor Microwave/Imager (SSMI) data of wind and atmospheric humidity as described in this issue of Flux News by Bentamy et al. (2008). We use the latest knowledge on atmospheric surface layer flux parameterization for calculating fluxes and for adjusting comparison data for atmospheric stratification (e.g. Drennan, 2006.) The missing components have been the radiative fluxes. The most variable components with a strong diurnal cycle are the shortwave radiative fluxes. The plan is to derive these from geostationary satellites as described in this issue of Flux News by Pinker et al. (2008). The strategy is to use the most advanced satellite observations relevant to the Atlantic Ocean such as those made from Meteosat-8 and at the same time, to utilize longer term satellite observations from earlier Meteosat missions so that longer term time series can be produced to match at least the 15 year period for which latent and sensible heat fluxes are available. Using radiative fluxes from a period of overlap between the two geostationary satellite systems of Meteosat-7 and -8 (2004-2006) the radiative flux calculations can be inter-calibrated.

An important new aspect in the derivation of the shortwave, SW, fluxes is the inclusion of aerosol effects over the tropical Atlantic, known to have an impact on such fluxes and also known to be transported over the entire Atlantic (e.g. Prospero 2001). Inference schemes for SW fluxes are being modified so that a full representation of aerosol properties can be incorporated, including their absorbing properties and vertical distributions. It is hoped that once additional information will become available from new satellite platforms (e. g. the A-Train) it will be possible to fully utilize these methods. Longwave fluxes are currently estimated with existing methods and implemented with new satellite observations. However, work is in progress to revisit these methods.

The importance of sea surface temperature, SST, for this effort has brought extra attention to retrieving the SST from the SEVIRI instrument on Meteosat-8. Differences between existing SST estimates and those developed for SEVIRI have been shown to exist for the Tropical Atlantic region. An effort will be made to link this aspect of our activity to the Global Ocean Data Assimilation Experiment, GODAE High–resolution SST Pilot Project (see Donlon et al. 2007) under the auspices of the World Climate Research Program.

We have used previous turbulent flux data sets to analyze wind and evaporation patterns in the tropical Atlantic (e.g. Katsaros et al. 2003) and have additional regional studies of climatic variables in the Atlantic and the Intra-Americas Sea in mind with the new longer and more complete heat flux data set. We will build on earlier work by Xie and Carton (2004), Mestas-Nuñez et al. (2005) and others.

Acknowledgments

This Collaborative Research, Atlantic Air-Sea Fluxes from Satellites: Their Variability and Analysis of Ocean Models, is supported under grant ATM0631685 from the U.S. National Science Foundation with funding to the University of Miami and the University of Maryland.

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Atlantic Air-Sea Fluxes from Satellites, their Variability and Analysis of Ocean Models: Radiative Fluxes

Kristina B. Katsaros, Rachel T. Pinker, James Carton, Abderrahim Bentamy, William M. Drennan, and Alberto M. Mestas-Nuñez

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Background

The primary goal of our activity is to evaluate, as accurately as possible, the total surface momentum, energy and mass budget over the tropical and subtropical Atlantic Ocean as described in Katsaros et al. (2008) (this issue). Net radiative fluxes, both short-wave (SW) and long-wave (LW) are part of this budget, the SW being the dominant part. Sea Surface Temperature (SST) plays an important role in this budget by regulating the turbulent heat fluxes and the outgoing LW component. In this brief summary reviewed will be steps taken to improve estimates of radiative fluxes over the Atlantic Ocean. The emphasis will be on the SW fluxes due to their dominant role in the budget.

The ultimate goal is to produce such fluxes for a fifteen year period for which sensible and latent heat information is available (Bentamy et al. 2008). The focus of present study is to develop inference schemes for improved estimates of radiative fluxes from satellite observations of high spatial and/or temporal resolutions.

Radiative Fluxes

Steps that have been taken include:

1. Production of high resolution SW Fluxes

The University Maryland/Shortwave Radiation Budget (UMD/SRB) Model was modified for use with observations from Meteosat-7. Modifications included development of cloud screening to separate clear and cloudy sky conditions and incorporation of detailed aerosol information into the inference scheme (Liu and Pinker 2007).

Total cloud amounts are derived from Meteosat-7 satellite observations using a 2-channel cloud detection scheme based on the Clouds from AVHRR (CLAVR) algorithm (Stowe et al. 1999). The cloud detection is performed at pixel-level (5 km) resolution, and then re-projected onto a 0.125° latitude-longitude grid.

A prototype of aerosol information that is needed for the implementation of the UMD/SRB model has been developed by Liu et al. (2005; 2007). It includes monthly mean values of the extensive property ($\tau_{0.55\mu m}$) and of the intensive parameters (single scattering albedo, asymmetry parameter and normalized extinction coefficients averaged at five spectral intervals (0.2-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7 and 0.7-4.0 μm). This information has been obtained by merging information from the Moderate Resolution Imaging Spectroradiometer (MODIS) retrievals, Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model simulations (Chin et al., 2002), and AErosol RObotic NETwork (AERONET) measurements. Specifically, global-scale estimates of aerosol optical depth at 0.55 μm is achieved by combining the accurate point measurements from AERONET and the spatial and temporal variation patterns from model and satellite data. Single scattering albedo is calculated by extrapolating the GOCART monochromatic value at 550nm to the entire solar spectrum using the spectral variation deduced from AERONET almucantar retrievals. Global-scale asymmetry parameter is estimated from MODIS Ångström exponent based on an empirical relationship derived from AERONET data. Normalized extinction coefficient is computed from

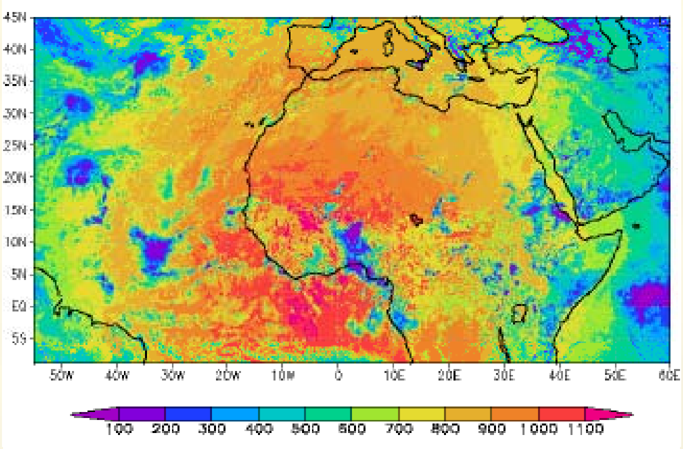

Figure 1. Shortwave fluxes (Wm^{-2}) from Meteosat-7 at 0.5^0 1 Sep 05, 2005 12 UTC. Using aerosol information as described by Liu et al. (2005; 2007).

Ångström exponent. It is also feasible to incorporate further improvement of aerosol characterization from independent sources once they become available.

Auxiliary information on the atmospheric state is taken from the NCEP/DOE-R2 reanalysis data (Kanamitsu et al. 2002). The year 2004 was selected for implementation since then Meteosat-8 observations begin and overlap with Meteosat-7 till the spring of 2006 when Meteosat-7 is fully replaced by Meteosat-8. The overlap period between the two satellites will facilitate the production of longer time series of SW radiative fluxes from the full resolution information of Meteosat-7 and from the reduced resolution of ISCCP DX (Rossow and Schiffer 1991) which are available for a period of over twenty years. Results for July 2004 are shown in Figure 1. The new inference scheme was tested both with nominal information on aerosols and with updated information on aerosols. The impact of aerosols on the

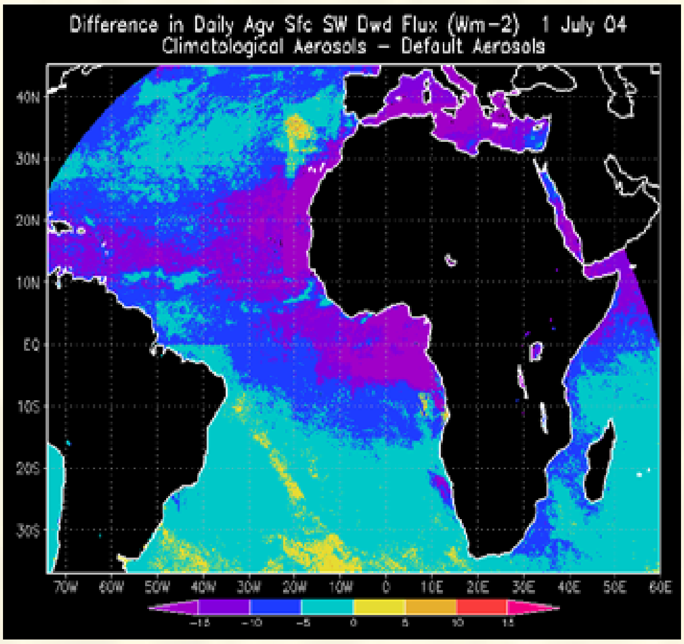

Figure 2. Difference in daily average surface SW flux (W/m^2) for July 1, 2004 using a new aerosol schemes and default aerosols. The updated information on aerosol properties used is described in Liu et al. (2005) and Liu et al. (2007) while the inference scheme for incorporation of the aerosol information is described by Liu and Pinker (2007).

SW surface radiative fluxes under all sky conditions is shown in Figure 2. For daily values, the reduction in this case was up to 15 W/m^2 and it extended across the Atlantic Ocean.

Information on aerosol optical depth as available from the Multiangle Imaging SpectroRadiometer (MISR) (Kahn et al. 2005) is shown in Figure 3. As evident, there is a good correspondence between the area of reduced SW fluxes and the spatial distribution of aerosol optical depth based on independent aerosol information.

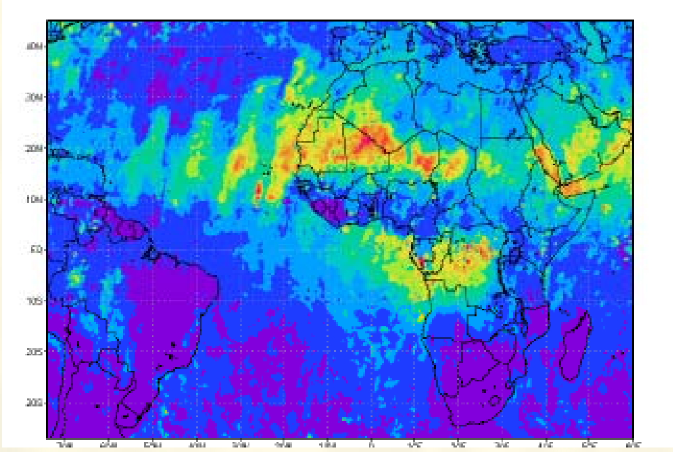

Figure 3. Distribution of aerosol optical depth for July 2004 as derived from MISER (Kahn et al. 2005).

2. Production of LW Fluxes

Down-welling LW fluxes are computed from microwave observations from SSM/I and implemented with the methodology of Schlüssel et al. (1995) at high resolution of (1/30). For computing the upwelling LW, there is a need for information on SST. Initially, available sources (such as Reynolds or AVHRR) are used to be subsequently replaced by a newly developed algorithm for SEVIRI which will provide very high resolution information that represents the diurnal cycle (Pinker et al. 2007).

3. Net surface fluxes and heat storage

Net surface fluxes are being produced by combining sensible and latent heat fluxes as derived by Bentamy et al. (2007) and the net radiative fluxes produced as described above. These fluxes will be eventually evaluated against the heat storage as derived from the SODA (Carton and Giese, 2007) reanalysis as well as from other model output. These fluxes will be eventually evaluated against the heat storage as derived from the SODA (Carton and Giese, 2007) reanalysis as well as from other model output. An example of the SODA estimates of seasonal heat storage is shown in Figure 4. Here the most evident feature is the seasonal heating of the summer ocean and cooling of the winter ocean. Along the equator the eastern ocean loses heat due to zonal advection in late-boreal spring and gains it back again in late fall. Coastal zones off Northwest Africa, Namibia, and the Patagonian shelf, also have distinct seasonal cycles associated with seasonal shifts in the alongshore winds.

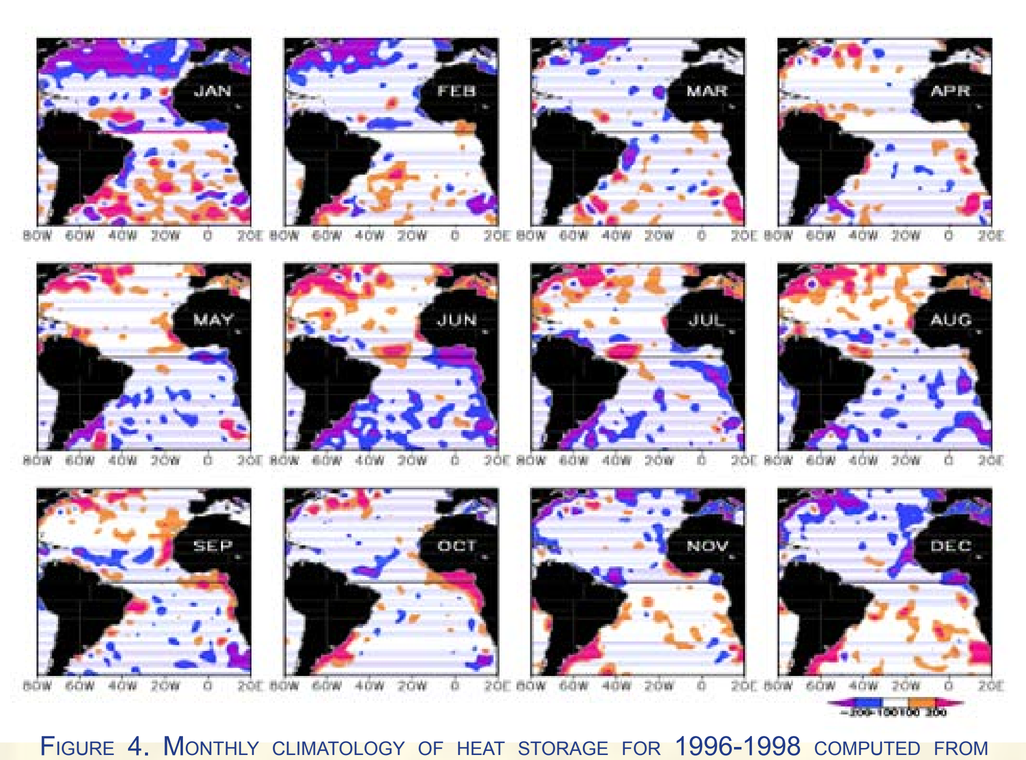

FIGURE 4. MONTHLY CLIMATOLOGY OF HEAT STORAGE FOR 1996-1998 COMPUTED FROM SODA 2.0.2 TEMPERATURES AT 0.25 DEGREE RESOLUTION. STORAGE IN EXCESS OF 100Wm^{-2} IS SHADED. HEAT GAIN IS REPRESENTED WITH WARM COLORS.

Acknowledgments

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15 Years of Ocean Surface Momentum and Heat Fluxes from Remotely Sensed Observations

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Introduction

The main surface variables involved in the air-sea exchange of energy are wind stress and turbulent (latent and sensible) heat fluxes. Quality estimates of these variables are essential for improving modeling simulations of climate variations and studies of oceanic dynamical processes. Radars and radiometers onboard satellites provide global measurements valuable for estimating turbulent fluxes. The methodology is based on physical properties of active and passive satellite instrument measurements, empirical and inverse models relating satellite observations and surface parameters, and objective analysis merging various satellite estimates. A high-resolution dataset for 1992 - 2006 is prepared for global Ocean at a spatial resolution of 1º, and weekly and monthly temporal resolutions. The satellite data come from the European Remote Sensing satellite scatterometers (ERS-1 and ERS-2), NASA scatterometers (NSCAT and Seawinds onboard ADEOS-1 and QuikScat, respectively), and several defense Meteorological Satellite Program (DMSP) radiometers (Special Sensor Microwave/Imager [SSM/I] F10 - F15). The reliability of the derived surface winds and heat fluxes is examined and validated through comprehensive comparisons with available in-situ data. The results are compared to NCEP/NCAR re-analysis and to ECMWF Analysis and re-analysis (ERA-40) wind and heat estimates. Comparisons are also performed with available global flux products estimated partly from remotely sensed surface parameters such as HOAPS (http://www.hoaps.zmaw.de/) and WHOI (http://oaflux.whoi.edu/) data.

Methodology

The remotely sensed winds and latent heat fluxes are primarily derived from the scatterometers onboard the European Remote Sensing Satellites (ERS-1 and ERS-2), NASA scatterometer (NSCAT) onboard ADEOS-1, Seawinds scatterometer onboard QuikSCAT, and from the radiometers onboard the Defense Meteorological Satellite Program (F10, F11, F13, F14, and F15). Sea surface temperature (SST) comes from NOAA weekly product (www.emc.ncep.noaa.gov/research/cmb/sst_analysis/) which is produced in a 1° longitude and latitude grid.

The first version of the IFREMER fluxes were described and validated by Bentamy et al (2003) and included only wind stress and latent heat flux. This dataset has been used to investigate spatial and temporal patterns of oceanic variability (Mestas-Nuñez et al, 2006) and to enhance the forcing of a global ocean circulation model (Ayina et al. 2006). These studies illustrated some of the advantages that satellite fluxes have compared to numerical flux estimates. However, they also showed that improvements are needed. For instance, it was shown that the transfer coefficients in bulk formulae, used to estimate satellite fluxes, are quite weak. The weakness of the transfer coefficient was related to the fact that the air-sea stability was not taken into account. This was due to the absence of satellite

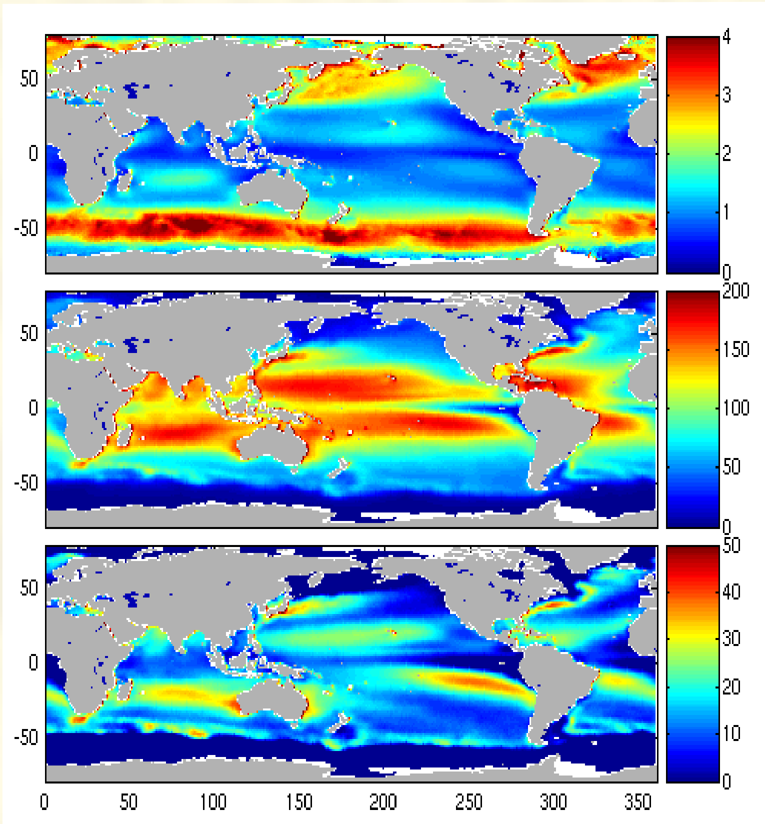

Figure1. Annual wind stress (top), latent heat flux (middle), and sensible heat flux (bottom) estimated from satellite observations during the period 1995–2000.

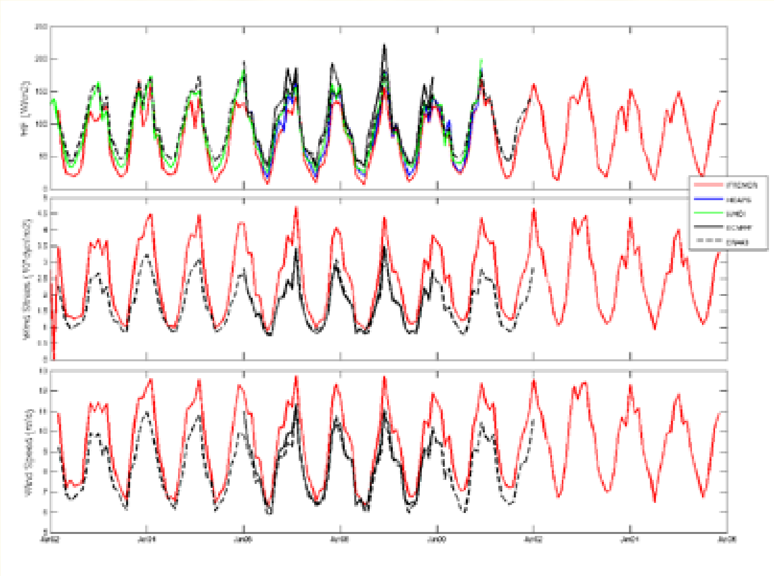

Figure 2. Time series of surface wind speed (bottom), wind stress (middle), and latent heat flux (top) estimates from IFREMER, HOAPS, WHOI, ECMWF, and ERA-40 during 1992 – 2006 and averaged over the north Atlantic oceanic area limited between 40°N and 55°N.

derived sea surface air temperature. In the new version, the former is estimated based on a Bowen ratio approach (Konda et al. 1996). Furthermore, the three turbulent flux components: surface wind stress, latent and sensible heat fluxes are estimated through the same iterative procedure. The revised algorithm is based on the Monin-Obukhov similarity theory which allows evaluation of the turbulent fluxes deduced from satellite retrievals with a correction of stability. The algorithm is validated using the multiyear hourly moored buoys data from the Tropical Ocean Global Atmosphere/Tropical Atmosphere Ocean (TOGA/TAO), Pilot Research Moored Array Tropical Atlantic (PIRATA), Oceanographic Data Acquisition Systems (ODAS) and National Data Buoy Center (NDBC) observation platforms, and is compared with the turbulent fluxes from existing algorithms such as COARE3.0 (Fairall, 2003), Smith (1988), and Large and Pond (1982). These comparisons show that the mean parameters agree well with those from COARE3.0, with correlations higher than 98%.

The fluxes are first estimated over a 1° grid over satellite swaths from available and valid daily-averaged remotely sensed retrievals: wind speed and vector-wind components, specific air humidity, air and sea surface temperatures. The latter bulk variables are used as a first guess for the bulk iterative procedure. Using an objective method requesting the determination and the knowledge of the spatial and temporal structure function of each variable, the turbulent fluxes are weekly and monthly averaged over the global ocean in a 1°×1° grid. Weekly and monthly averaged bulk variables are also calculated.

The present study employs the weekly- and monthly-averaged 1° x 1° fluxes available during the study period March 1992 – March 2006. Figure 1 shows annual mean of resulting surface wind stress (top panel), latent heat flux (middle panel), and sensible heat flux (bottom panel) calculated during 1992 – 2006. The accuracy of the resulting weekly fields is determined by comparisons with moored-buoy estimates, which are deployed and maintained by four different institutions in the Atlantic and Pacific oceans. The agreement between satellite and in-situ data is good enough to suggest that flux sources are meeting their accuracy goals. For instance, it was found that the satellite weekly zonal and meridional wind stress components, and latent heat flux exhibited the main known spatial and temporal characteristics at global as well as at regional scales. The regional variability of the three surface parameters is well revealed by the satellite time series in the tropics and in the North Atlantic (with respect to buoy and ship data). The mean and rms difference between buoy and remotely sensed flux estimates are quite small. For instance, in the tropics, the bias values for wind stress and latent heat flux are 0.510-2N/m^2 and 7.0W/m^2, respectively. The corresponding rms values are 1.5 10^{-2}N/m^2 and 29W/m^2.

At global scale, IFREMER are compared to fluxes derived from numerical model analysis or re-analysis such as ECMWF and ERA-40, or from existing flux products such as HOAPS and WHOI data. Figure 2 illustrates an example of the comparison results. It shows the time series of wind speed (bottom panel), wind stress amplitude (middle panel), and latent heat flux (top panel) from various sources averaged over the North Atlantic between 40°N and 55°N. The various sources exhibit similar temporal features. The main discrepancy is found in the amplitude. For instance, satellite wind stresses are higher than ECMWF and ERA-40, while both numerical models provide the highest estimates of latent heat flux. One main result that can be drawn from this figure is that there is no significant impact of satellite change on flux estimation.

Data

The derived fluxes are publicly available as weekly- and monthly averaged data on a 1° grid between 80°S and 80°N. The surface parameter fields are calculated globally, excluding sea ice areas. In order to determine the location of sea ice, the IFREMER/CERSAT weekly sea ice concentration is used. This parameter is estimated for both Arctic and Antarctic from the daily brightness temperature maps from SSM/I (ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/psi-concentration/).

The turbulent flux fields are calculated during the period March 1992 through March 2006. They are considered as test cases that will provide useful insight for production of high space and time resolutions at global and regional scales. Data are available at IFREMER and freely distributed (ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/flux-merged/flux/). This study is performed within MERCATOR (http://www.mercator-ocean.fr/) and MERSEA (http://www.mersea.eu.org) projects.

The data files are in NetCDF format supported by several scientific softwares.

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Implication from Recent Global Datasets about Decadal Variations of Global Energy and Ocean Heat Budget and Meridional Energy Transports





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We investigate what can be learned about how decadal-scale variations of the global energy budget at TOA are partitioned between the atmosphere and ocean and their mean meridional heat transports using the recent global, decades-long datasets, consisting of two satellite-derived top-of-atmosphere (TOA) and surface radiative flux datasets from the International Satellite Cloud Climatology Project Flux product (ISCCP-FD, version 0.0, covering 1983 to 2004, see Zhang et al., 2004) and the Global Energy and Water Cycle Experiment Surface Radiation Budget project (GWEX-SRB, release version 2.6 and 2.5 for SW and LW, respectively, covering 1983 to 2004 see Stackhouse et al., 2001), three ocean surface turbulent flux datasets from Goddard Satellite-based Surface Turbulent Fluxes (GSSTF, version 2, covering 1988 to 2000, see Chou et al., 2004), Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite data (HOAPS, version 2, covering 1981 to 2002, see Grassl et al., 2000) and Woods Hole Oceanographic Institution Objectively Analyzed air-sea Fluxes (WHOI, covering 1981-2002, see Yu et al., 2004) and one ocean heat storage rate dataset from Willis et al. (2004). Based on their information and comparisons of the above datasets, and Bentamy et al. (2003) and Willis et al. (2003 and 2004), the uncertainties for the different types of datasets are estimated in Table 1.

Although the uncertainties among the TOA radiative flux datasets are large enough (Table 1) that direct measurements of planetary energy imbalances are still unreliable, we compare the interannual anomalies of the ocean heat content (OHC) with those derived from ISCCP-FD and GEWEX-SRB planetary energy imbalances. In converting radiative fluxes to OHC, we first remove the bias from 1992-2001 and 1993-2000 mean for global TOA and oceanic surface, respectively. Figure 1 shows their excellent quantitative agreement of OHC between TOA flux-based and Willis observation-based, where the reference year is set to 1992 (all OHC = 0; mid-point is used for a yearly value in all the plots throughout the paper). These datasets, together imply a persistent heating of the upper ocean over at least the past decade and possibly the last two decades.

With the two surface net radiative flux datasets (FD and SRB) and three turbulent heat flux datasets (GSSTF, HOAPS and WHOI), we construct six total ocean surface energy flux (OSEF) datasets. Figure 2 shows the annual-mean OHC anomalies for the six OSEF-derived and Willis et al. for the period of 1993

Type of Data Sets	Uncertainty Estimate
Radiative Fluxes: TOA	5-10 (monthly, regional mean, 2-3 for global mean bias)
Radiative Fluxes: Surface	10-15 (monthly, regional mean)
Latent Fluxes	≥ 15-25
Sensible Fluxes	≥ 5 (or 50% in relative sense)
Total Ocean Surface Energy Flux	≥ 20-30
Ocean Heat Content	~ 0.12 (RMS error ~ 4.6 for Tasman Sea)

TABLE 1. UNCERTAINTY ESTIMATES (IN W/M²) FOR THE GLOBAL DATASETS USED IN THE STUDY BASED ON DATASETS INFORMATION AND THEIR COMPARISONS, BENTAMY ET AL. (2003), WILLIS ET AL. (2003 AND 2004).

- 2000 (referenced to 1993 = 0, different in addition to bias-removing period with Figure 1 so Willis OHC look differently in Figure 1 and Figure 2). The comparison of interannual anomalies of total OHC no longer shows such good agreement: the former generally indicating a cooling over the past decade as against the latter's general warming. This may be caused by too-large uncertainties of OSEF (Table 1).

From the TOA zonal-mean total net radiative flux, we can infer the mean meridional energy transport of the ocean-atmosphere system required for balancing local energy loss or gain using the Surface and Planetary Energy Balance (SPEB) method referred to in Zhang and Rossow (1997). Figures 3 and 4 show the interannual anomalies of the mean meridional heat transport by the atmosphere-ocean system inferred from the two TOA radiative flux datasets, FD and SRB, respectively, with respect to 93-97 mean (the period without El Niño events). Although each event is different in character, the most interesting features appear in that both showing similar dipole patterns of weakened poleward transport closely associated with the 1986/87, 1991/92 and 1997/98 El Niño events. All dipoles for the three El Niño events essentially show a weakening of poleward energy transports for both hemispheres (since positive transport means northward transport, decreased poleward transport is a negative anomaly in the northern hemisphere and a positive anomaly in the southern hemisphere) by up to about 0.25 petawatts (pW). The dipoles appear either nearly centered or in slight dislocations in time on the events. Also notable are the differing latitudinal positions and magnitudes of the dipoles: the dipoles are much closer to the equator in the 1991/92 event than during the 1997/98 event, which may be a consequence of the radiative effects of the Mt. Pinatubo aerosol, but the 1986/87 also has low-latitude dipoles with a much stronger anomaly in the southern than northern hemisphere. At the beginning of the 1982/83 El Niño event, which is asymmetric about the equator, there is also a hint of a perturbation associated with the El Chichon volcano. There is no obvious dipole for 2002/03 El Niño perhaps because the current FD and SRB data record ends in December 2004. That needs further study. We have also examined the corresponding ocean and atmosphere transport anomalies separately but they do not suggest conclusively, whether the transport anomalies occur primarily in the ocean or atmosphere because of the large uncertainties (Table 1). Nevertheless the lower-latitude features in Figures 3 and 4 might be predominantly ocean transport anomalies whereas the midlatitude features might be predominantly atmosphere transport anomalies but the current quality of the surface turbulent energy flux datasets precludes confirmation in the first place.

We believe that this analysis indicates that these

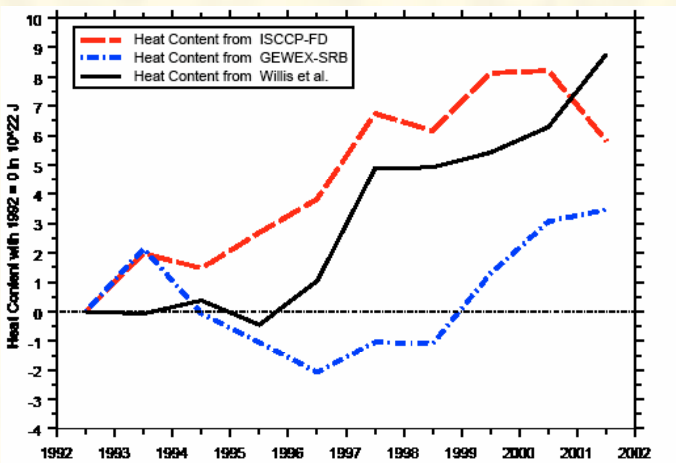

FIGURE 1. 10-YR (1992-2001) GLOBAL, ANNUAL-MEAN HEAT CONTENT (IN 1022 J): 1-YR-BACKED WILLIS ET AL. (SOLID BLACK, FROM ORIGINAL 1993-2004) AND THOSE CONVERTED FROM ORIGINAL TOTAL TOA NET RADIATIVE FLUX OF ISCCP-FD (DASHED RED) AND GEWEX-SRB (DOT-DASHED BLUE).

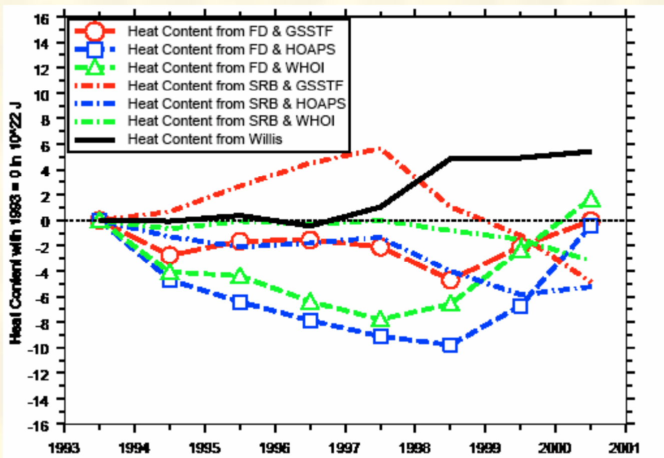

FIGURE 2. 8-YR (1993-2000) GLOBAL, ANNUAL-MEAN HEAT CONTENT (IN 1022 J): WILLIS ET AL. (SOLID BLACK) AND THOSE CONVERTED FROM TOTAL OCEANIC SURFACE ENERGY FLUXES: ISCCP-FD COMBINED WITH GSSTF (DASHED RED WITH OPEN CIRCLE), HOAPS (DASHED BLUE WITH OPEN SQUARE) AND WHOI (DASHED GREEN WITH OPEN TRIANGLE), AND GEWEX-SRB COMBINED WITH GSSTF (DOT-DASHED RED WITHOUT MARKS), HOAPS (DOT-DASH BLUE WITHOUT MARKS) AND WHOI (DOT-DASHED GREEN WITHOUT MARKS).

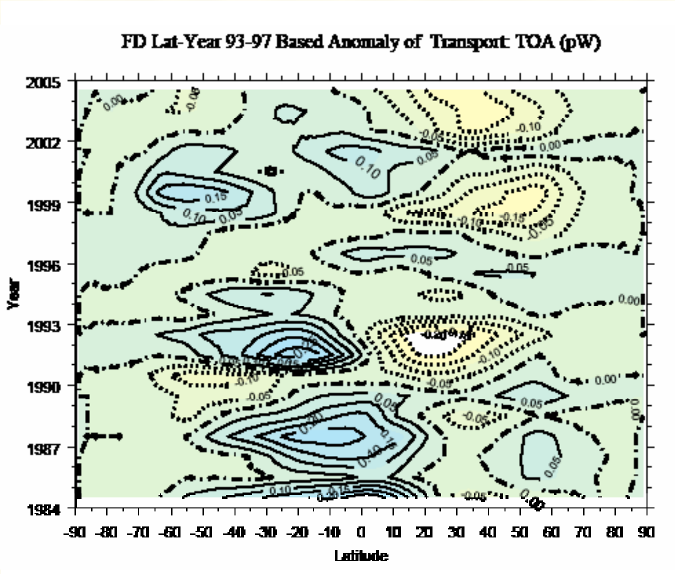

Figure 3. Latitude-Year contour anomaly map of the northward meridional energy transport (in Peta Watts) for the atmospheric-Earth system derived from annual-mean ISCCP-FD total TOA radiative flux (anomaly is based on 1993-1997 mean). Solid (dotted) is for Positive (negative) values with thick dash-dotted for zero line.

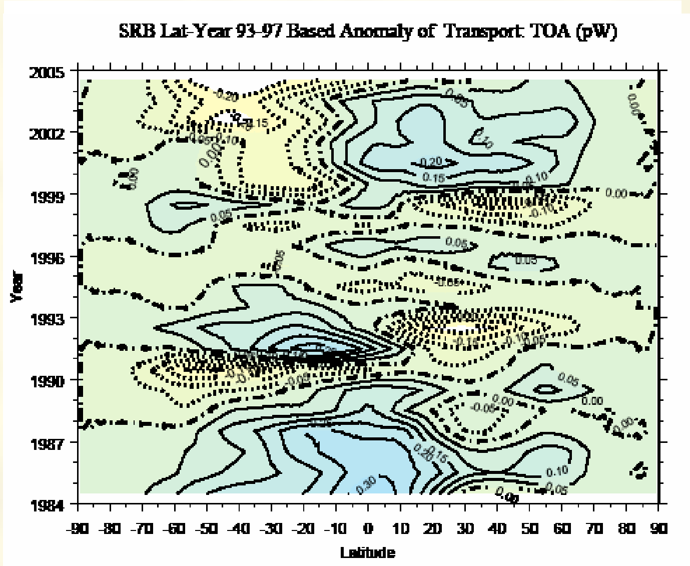

Figure 4. Latitude-Year contour anomaly map of the northward meridional energy transport (in Peta Watts) for the atmospheric-Earth system derived from annual-mean GEWEX-SRB total TOA radiative flux (anomaly is based on 1993-1997 mean). Solid (dotted) is for Positive (negative) values with thick dash-dotted for zero line.

products are showing some signs that may be useful for monitoring long-term energy budget variations and other climatological changes, and that it appears critically important to reduce their uncertainties enough to diagnose the variations of the coupling of the atmosphere and ocean heat exchanges and transports over decadal time scales.

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Latent Heat Flux and Ocean-Atmosphere Water Exchange

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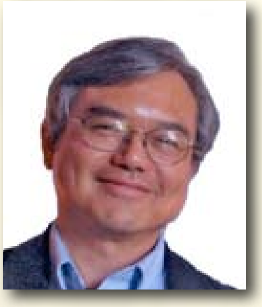

Introduction

Starting from the pioneering studies of Liu and Niiler (1984) and Liu and Gautier (1990), spacebased data have been used to estimate the latent and net heat exchanges between the ocean and the atmosphere. Spacebased data provide more uniform coverage and better temporal variations than ship climatology. Although improvements have been made in the past decades by other investigators, considerable biases among various components of the exchanges remain, whether from ship measurements, satellite data, or numerical models. Recently, we have made major improvements in estimating high-resolution evaporation (E) and the integrated moisture advection (**Θ**). The divergence of **Θ** is equal to E-P, where P is the precipitation, when averaged longer than a few days. Achieving closures on the water balance in the atmosphere and the heat and mass balance in the ocean helps us to validate our results.

Methodology

The computation of the moisture transport integrated over the depth of the atmosphere

$$\Theta = \int_0^{p_s} q\mathbf{u}\, dp \qquad (1)$$

where p is the pressure and p_s is the pressure at the surface, requires the vertical profile of specific humidity (q) and wind vector **u**, which are not measured by spacebased sensors with sufficient resolution. **Θ** can be viewed as the column of water vapor,

$$W = \frac{1}{g}\int_0^{p_s} q dp \qquad (2)$$

advected by an effective velocity $\mathbf{u}_e$, so that $\Theta = \mathbf{u}_e W$, and $\mathbf{u}_e$ is the depth-averaged wind velocity weighted by humidity. Bold symbols represent vector quantities, and g is the acceleration to gravity.

W has been measured rather accurately by microwave radiometers. Improved methods were developed to related $\mathbf{u}_e$ to the equivalent neutral wind measured by QuikSCAT, $\mathbf{u}_s$, based on neural network (Liu and Tang, 2005) and to $\mathbf{u}_s$ and cloud-drift winds at 850 mb, based on support vector regression (Xie et al. 2007). The latest method significantly reduces both mean and standard deviation of the difference between **Θ** derived from the statistical model and from rawinsonde observations, from synoptic to seasonal time scales. Surface latent heat flux and E could be computed by removing P from $\nabla\cdot\Theta$.

We pioneered the method of estimating E, through bulk parameterization (e.g., Liu and Niiler 1984; Liu et al. 1994) two decades ago, using only spacebased observations. In bulk parameterization, E depends on surface wind speed, sea surface temperature (SST), and near surface humidity. Mircrowave radiometers measure wind speed, SST, and W. Surface humidity was first related to W through a statistical relation by Liu (1986). The rationale is that the vertical distribution of humidity is sufficiently coherent at low frequency (Liu et al., 1991). We are also improving and validating a method to retrieve E directly from the measured radiances, as first demonstrated by Liu (1990).

There were considerable differences among many precipitation data products in the past, but continuous improvement has put them closer to each other. Standard products from the Tropical Rain Measuring Mission (TRMM) (Kummerow et al. 2000) were used in this study.

Conservation Principles

While sufficient coverage and resolution of **Θ** and E can be best achieved from the vantage point of space, the validation of spacebased measurements has always been difficult because there is a lack of appropriate standards. While various components of ocean-atmosphere water and heat exchanges, including **Θ** and E, have been validated through point comparison with in situ measurements, useful scientific application may be the best validation of their usefulness. The closure of water and heat balances is a good way of validation, besides the characterization of the water and energy cycles.

Figure 1 shows that the annual mean of $\nabla\cdot\Theta$ bears similar large-scale features as that of E-P, over the ocean between 40°S-40°N. The agreement, not only in geographical variation but also in magnitude of the two terms, derived from separate methods, is extremely encouraging, and it is the best validation of both methodology and satellite observations. The agreement in intraseasonal time scales at two typical locations is evident in Figure 2. The agreements in the annual cycle and the semi-annual cycles are also shown in the tropical and equatorial regions respectively.

GRACE (Gravity Recovery and Climate Experiment) is a geodesy mission to measure Earth's gravity field, but the variation of the gravity field are largely the result of the change of water storage. Using GRACE mass change rate ($\partial M/\partial t$), **Θ**, and climatological river

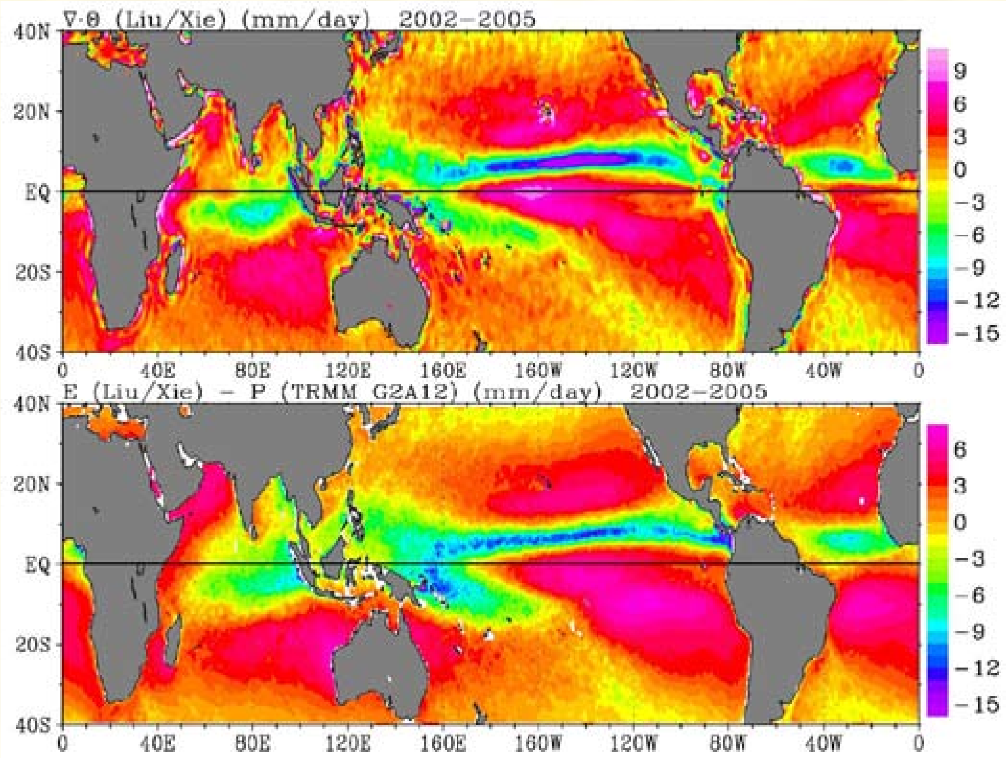

Figure 1. Annual mean of (a) $\nabla \cdot \Theta$ and (b) E-P in mm/day, averaged from 2000-2004, derived from QuikSCAT, SSM/I, and TRMM Microwave Imager (TMI).

discharge (R), Liu et al (2006) first demonstrated the continental water balance in South America. Figure 3 shows $\partial M/\partial t$ integrated over all ocean area, balances $\nabla \cdot \Theta$ integrated over the same ocean area minus the line-integral of R over all coastline, both in magnitude and in phase.

If the change of heat storage in the ocean is negligible in long-term average, the heat exchanges with the atmosphere has to balance the heat divergence according to the conservation principle. For an ocean basin, such as the Atlantic or the Pacific, bounded by a latitude circle in the south and the continental mass in the north, the area integral of surface heat flux would give the time varying meridional heat transport (MHT) in the ocean. The large uncertainties in long term annual mean of MHT compiled in past studies are clearly demonstrated in Figure 4. In a preliminary study, the MHT computed from our spaced surface heat flux (red line) falls within

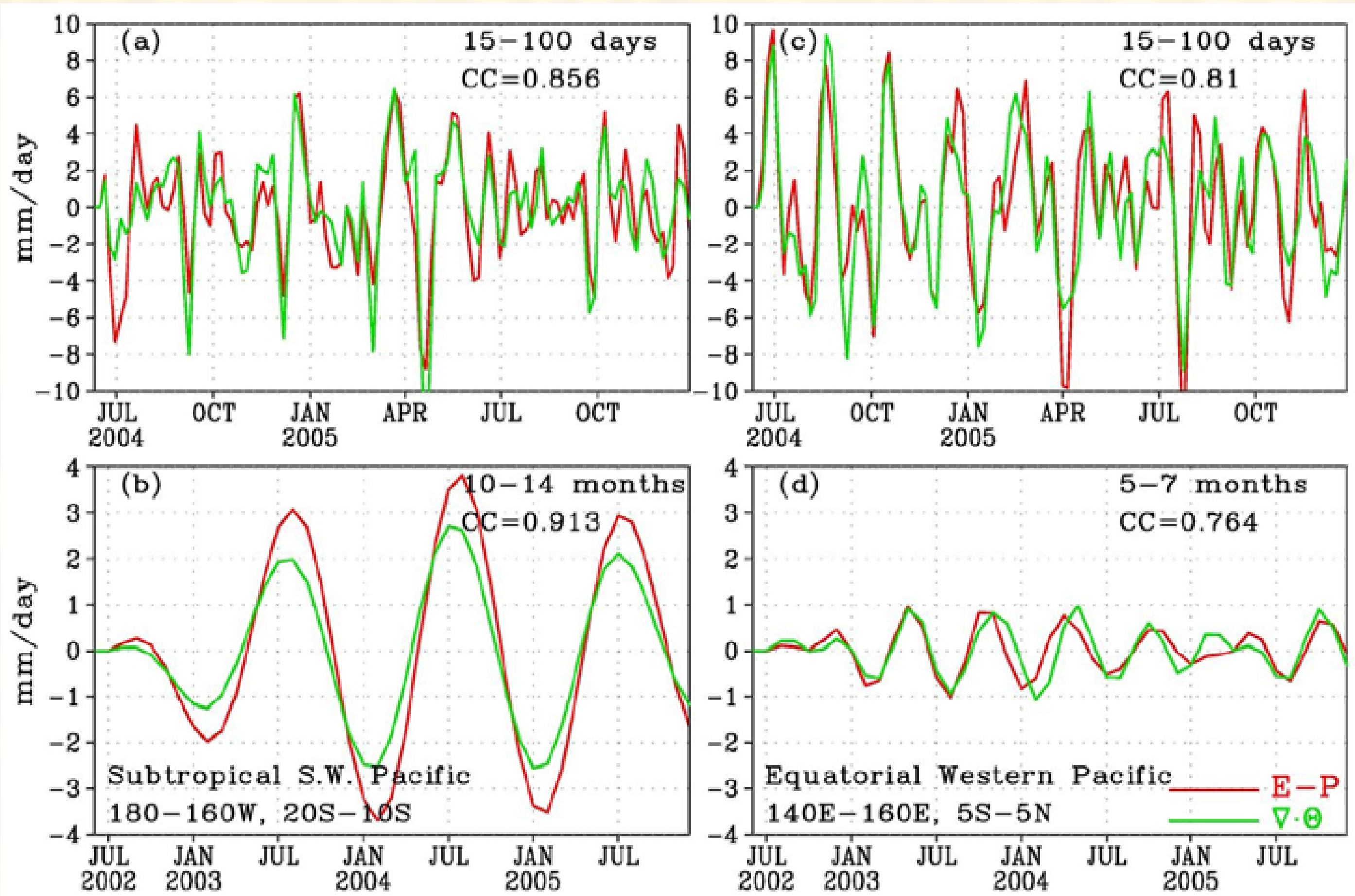

Figure 2. Band-pass filtered time series of $\nabla \cdot \Theta$ (green curve) and E-P (red curve) over South Pacific convergence zone for (a) 15-100 days, (b) 10-14 months, and over equatorial western Pacific for (c) 15-100 days, (d) 5-7 months.

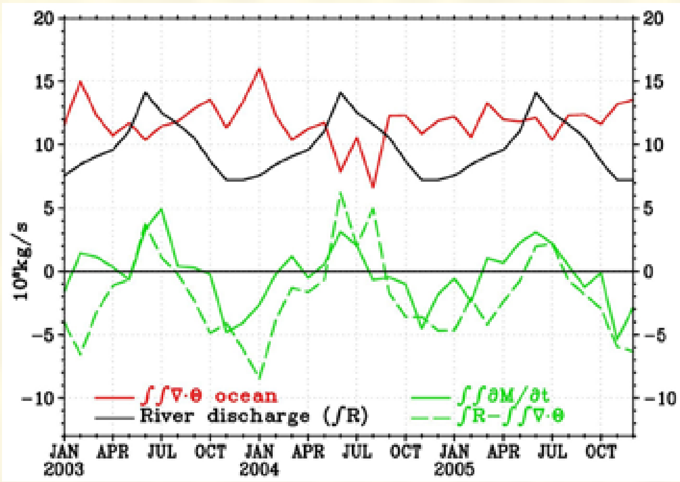

FIGURE 3. ANNUAL VARIATION OF HYDROLOGIC PARAMETERS AVERAGE OVER THE GLOBAL OCEAN: MASS CHANGE RATE $\iint \partial M/\partial t$ (SOLID GREEN LINE) AND $\iint \nabla\cdot\Theta$ (RED LINE), SUM OF CLIMATOLOGICAL TOTAL RIVER DISCHARGE ACROSS ALL COASTLINE $\int R$ (SOLID BLACK LINE), AND $\int R - \iint \nabla\cdot\Theta$ (DASHED GREEN LINE).

the large scatter of the old results. Our MHT is lower than those from the simulation of the Estimating the Circulation and Climate of the Ocean (ECCO) model (Fukumori 2002) (green line) between the equator and 30°N and higher than ECCO between 30°N and 50°N. It agrees with ECCO surprisingly well south of the equator.

Conclusion

Using spacebased estimation of E and Θ, we have demonstrated the approximate atmospheric water balance both in magnitude and in phase, from intraseasonal to annual time scales, the mass balance of global ocean in annual variation, and the heat balance of the Atlantic Ocean in the annual mean. The agreements with major conservation principles show the advances we have made in synergistic application of spacebased measurements to estimate ocean-atmosphere exchanges.

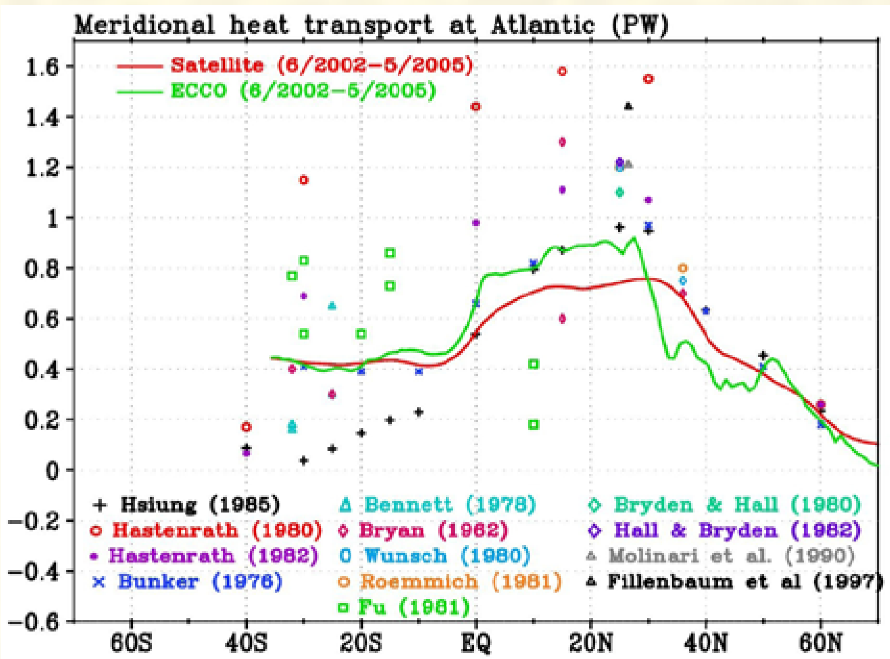

Figure 4. Comparison of annual mean MHT in the Atlantic as a function of latitude. Red curve is calculated using the surface heat flux from satellite observations. The green curve is computed from ECCO data. Values marked by various symbols and colors are from past studies, derived either from the surface heat flux or hydrographic measurements.

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Surface Turbulent Flux Product Comparison

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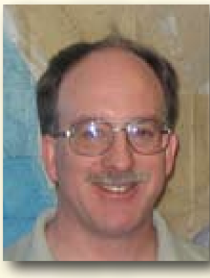


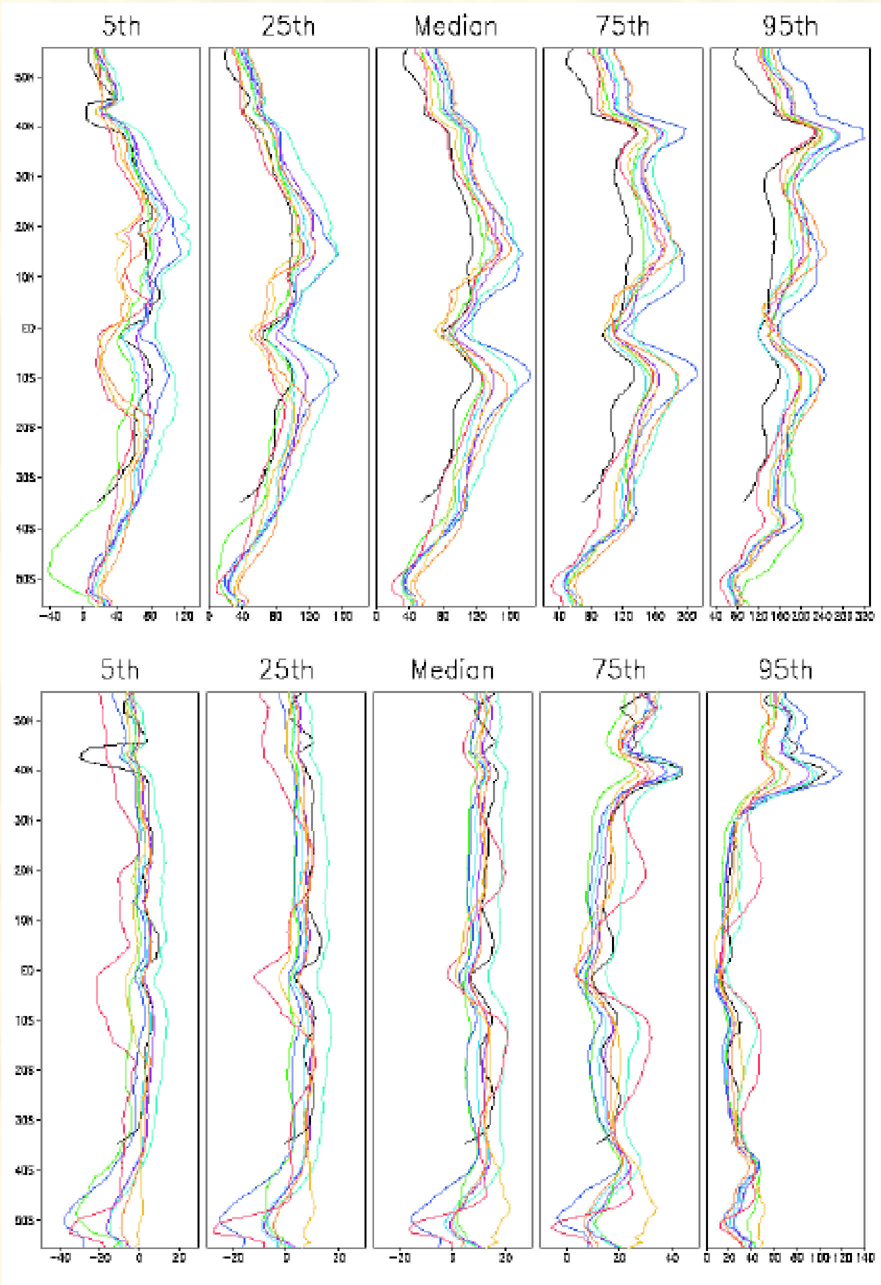
There are many types of products that include turbulent fluxes of latent heat, sensible heat, and stress. It is often difficult for people using surface fluxes to judge which type of product is appropriate for their application. Reanalysis products, created from numerical weather prediction (NWP) models with fixed model physics (albeit with changing data products for assimilation), are often used because of the spatial/temporal coverage and the additional information provided at various levels in the atmosphere. However, such models have poor representations of the atmospheric boundary layer, questionable parameterizations of surface turbulent stresses, and assimilate only a small fraction of marine surface observations. In data-sparse areas such as the Southern Ocean, storms tend to appear as they approach populated areas (such as Australia) and rapidly disappear after they pass these areas of greater in situ observation density (Hilburn et al. 2003). Satellite derived products benefit from the much better spatial sampling (and in some locations better temporal sampling) of winds and sea surface temperatures. However, the satellite-derived fluxes are subject to uncertainties associated with the retrieval algorithms and questionable estimates of atmospheric temperature and humidity. Products based on ship and buoy observations provide a longer time series than the satellite based products (beneficial for climate studies), but suffer from often poor and inhomogeneous sampling and uncertainties inherent in ship observations. An evaluation of surface forcing products is one of the SeaFlux goals. Ongoing flux comparisons at the Florida State University help illustrate strengths and weaknesses of selected products; it should help users trying to choose among these products find a match to their objectives.

Monthly averaged surface turbulent fluxes (stress, sensible heat, and latent heat) are compared for nine products (see Table 1). Reanalysis products include NCEPR2 (Kanamitsu et al. 2002), JRA25 (Onogi et al. 2007), and ERA40 (Uppalla et al. 2005). Satellite derived products include IFREMER and HOAPS2 (based on method of Grassl et al. 2000). The HOAPS2 variables examined herein are identical in the HOAPS3 product. Products based on ship and buoy observations include FSU3 (adapted from the method of Bourassa et al. 2005) and NOC1.1 (formerly SOC; Josey et al. 1998). Hybrid NWP model and satellite products include WHOI (Yu and Weller 2007) and GSSTF2 (Chou et al. 2003). These products were chosen because they are freely available, reasonably easy to obtain, and reasonably homogeneous throughout a common comparison period. The common period of March 1993 through December 2000 is examined. When available (Table 1), the parameters needed to calculate the fluxes (winds, air and sea temperature, and specific humidity) are also compared. Each product has been regridded onto a 1x1° grid. To reduce problems related to land, data within two grid cells of land are not used in this comparison.

Preliminary results show very large differences in

Product	LHF	SHF	Stress (x,y)	Wind Speed	u wind	v wind	T air	Q air	SST	Product Type	Grid Spacing
NCEPR2	x	x	x		x	x	x	x	x	Reanalysis	Gaussian (T62, 194x94)
JRA25	x	x	x		x	x	x	x	x	Reanalysis	(T106L40) ~120km
ERA40	x	x	x		x	x	x	x	x	Reanalysis	1 1/8 degrees
WHOI	x	x								Hybrid	1 x 1 degree
GSSTF2	x	x	x	x				x		Hybrid	1 x 1 degree
IFREMER	x	x	x	x	x	x	x	x	x	Satellite	1 x 1 degree
HOAPS2	x	x		x				x	x	Satellite	0.5 x 0.5 degree
FSU3	x	x	x	x	x	x	x	x	x	In-situ	1 x 1 degree
NOC1.1	x	x	x	x			x	x		In-situ	1 x 1 degree

Table 1. Monthly averaged surface turbulent flux products and associated parameters used for intercomparison.



FSU WHOI NOC NCEPR2 JRA ERA40 IFREMER GSSFT2 HOAPS

Figure 1. Distributions (5th, 25th, 50th, 75th, and 95th percentiles) of contributions to zonally averaged latent (top) and sensible (bottom) fluxes for the Atlantic Ocean. The large spread in the products over the tropical North Atlantic (5°N to 15°N) is further examined in Figure 2.

the distribution of the zonally averaged turbulent heat fluxes for all ocean basins (Figure 1). The differences in the zonal averages are large from the point of view of climate modeling, where biases >10 Wm^{-2} (including radiation fluxes; WCRP 1989; Webster and Lukas 1992) are considered serious problems. Figure 2 compares the distributions of the latent and sensible heat fluxes over the tropical North Atlantic, and shows variations between the products at all examined quantiles. Differences in the products can result from the input parameters and the methodology used to produce the turbulent flux fields (i.e., objective techniques and bulk flux algorithms). Similar plots (not shown) for temperature and specific humidity show very large differences. Accurate air temperature retrievals and consequently the derived sensible heat flux fields are currently weak areas in the purely satellite based products. The means of the turbulent heat fluxes and derived quantities show similar patterns (except for the purely satellite derived sensible heat flux); however, the standard deviations (not shown) reveal problems associated with objective techniques and the data assimilation. For example, the TAO buoy array is easily identified in the ERA40 and NOC products. Ship tracks are seen in the FSU3 and NOC products. However, in the North Atlantic Ocean, where the ship coverage is much better, the ship tracks are not easily identified in the FSU3 fields. Other unrealistic features include the orographically induced ringing in the NCEPR2, JRA25, and GSSTF2 products.

These results are based on monthly averaged fluxes; therefore, they likely underestimate the issues with fluxes produced for shorter time scales. The large differences in fluxes, and in the spatial / temporal

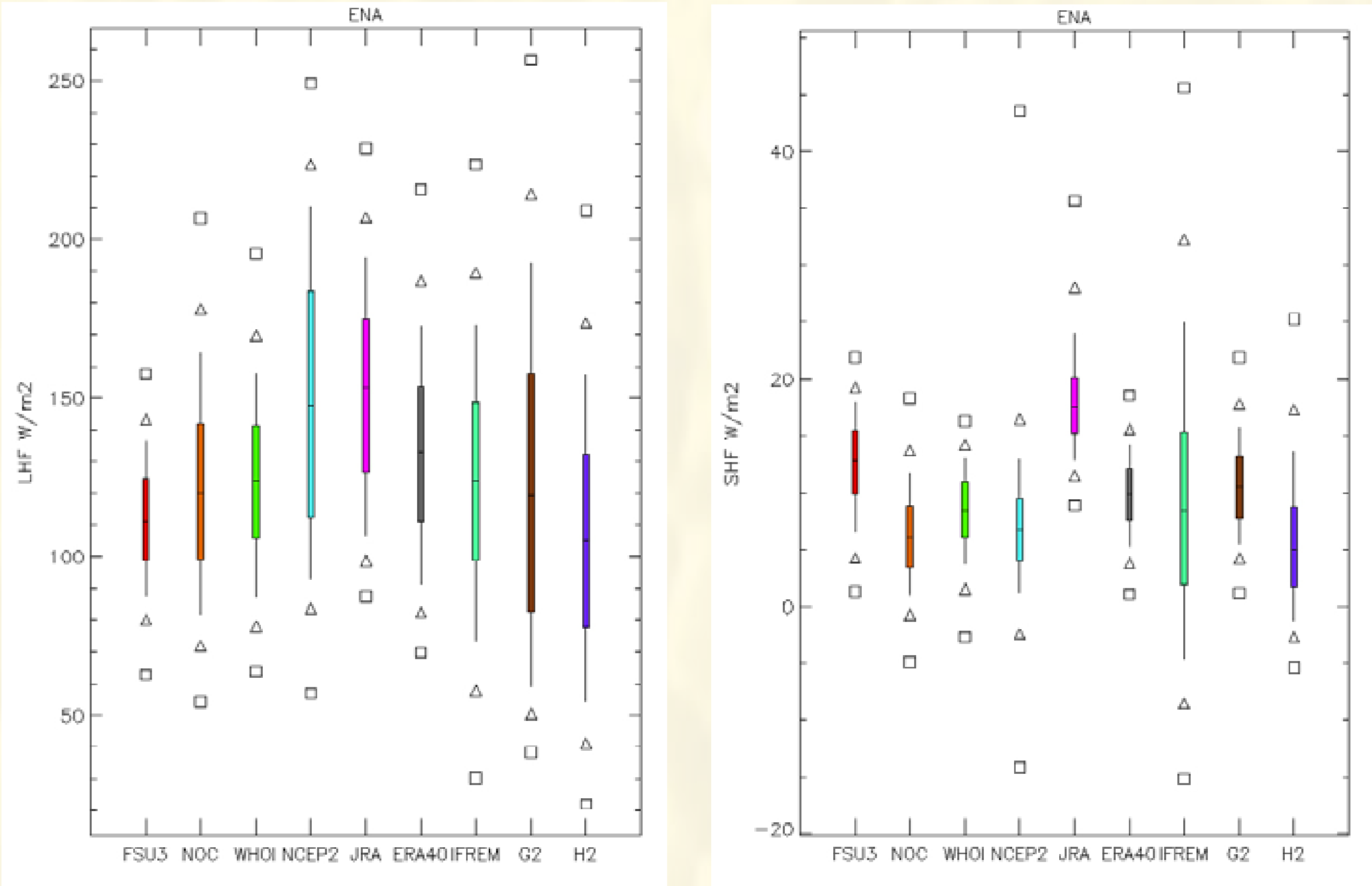


FIGURE 2. BOX-AND-WHISKER PLOTS OF THE TURBULENT HEAT FLUXES FOR THE TROPICAL NORTH ATLANTIC (5°N TO 15°N): (LEFT) LATENT HEAT FLUX (W M^{-2}), AND (RIGHT) SENSIBLE HEAT FLUX (W M^{-2}). THE UPPER AND LOWER ENDS OF THE BOXES ARE DRAWN AT THE 75TH AND 25TH QUARTILES RESPECTIVELY AND THE BAR THROUGH THE BOX IS DRAWN AT THE MEDIAN. THE WHISKERS EXTEND FROM THE QUARTILES TO THE 90TH AND 10TH PERCENTILES. THE TRIANGLES (SQUARES) REPRESENT THE 95TH AND 5TH (99TH AND 1ST) PERCENTILES RESPECTIVELY. G2 (H2) REPRESENTS THE GSSTF2 (HOAPS2) PRODUCT.

changes in these products indicate that there are still serious challenges to overcome in the construction of surface forcing fields for applications in climate and general oceanography.

Acknowledgments

We thank the many people that made their products available for comparison, and who were involved in preliminary discussions of how comparisons could be made. We also thank the NOAA Climate Observation Division and NSF Physical Oceanography for supporting this effort.

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Blended High Resolution Sea Surface Flux Parameters from Multiple Satellites

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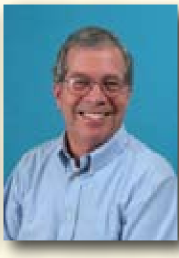

Summary

This paper describes globally gridded high resolution air-sea flux related parameters that are blended from observations of multiple platforms (ships, buoys, satellites, etc). The integrated use of multiple-platform observations reduces both systematic bias errors and analysis errors of the blended products. A sampling study was first carried out for the feasibilities of producing various high resolution gridded products for sea surface wind speed using up to six satellite observations. Consequently, global 0.25° gridded sea surface wind speeds are produced for temporal resolutions of 6-hourly and daily. For many oceanography applications that use vector winds, wind directions are added from NCEP Reanalysis 2. The hybrid vector winds are available from July 1987 onward. The widely used NOAA/Reynolds Optimum Interpolation (OI) SST analysis has improved from 1° and weekly to 0.25° and daily and uses both microwave and AVHRR satellite observations. The SST products are available from Jan 1985 onward. A neural network approach is used to develop the retrievals of sea surface air temperature (T_a) and humidity (Q_a) from the AMSU sounder onboard the NOAA series of satellites. Blended 6-hourly and 0.5° (Q_a) or 1° (T_a) gridded products are being produced and will be available from 1998 onward. Data description and access can be found from the links at http://www.ncdc.noaa.gov/oa/satellite.html.

Introduction

Advances in understanding the coupled air-sea system and numerical modeling of the ocean and atmosphere demand increasingly higher resolution data over the global ocean surface. Some applications require that fluxes be computed at temporal and spatial resolutions of up to 3 hours and 50 km (e.g., Curry et al. 2004). Observationally, these requirements can only be met by utilizing multiple satellite observations of sea surface wind (SSW), sea surface temperature (SST), and sea surface air temperature and humidity (T_a and Q_a) for the computation of turbulent (latent and sensible) heat fluxes via empirical formulae. Efforts to generate such high resolution products from multiple-satellite and in-situ observations on an operational basis have been started at the U.S. National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC). Here we report the feasibility study, current product status and available data services.

Sea Surface Winds

Sea surface wind speed has been observed from long-term multiple satellites, ranging from one in the mid 1987 to six or more since mid 2002 (Figure 1). Detailed sampling studies showed that on a global 0.25° grid, blended products with temporal resolutions of 6-hours, 12-hours and daily have become feasible since mid 2002, mid 1995 and January 1991, respectively (Zhang et al. 2006). Thus four times per day global 0.25° snapshots have been produced since mid 1987 using spatial and time windows of 125 km and 12-hours. A 3-D near Gaussian interpolation was used to minimize aliases for the 6 times per day instantaneous fields.

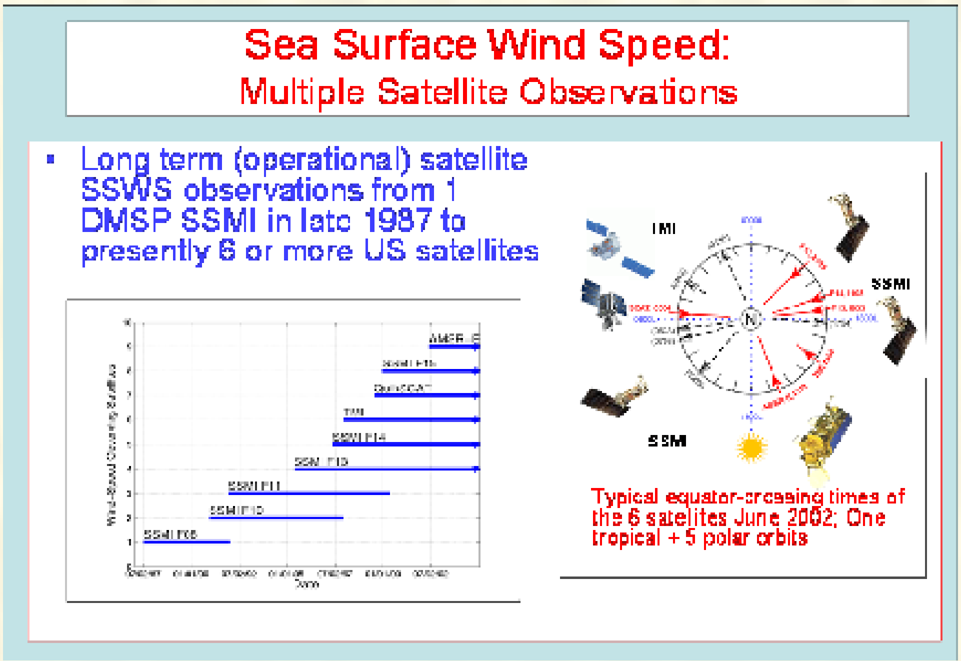

Figure 1. Timelines and tracks (schematic) of satellites that observe sea surface wind speeds.

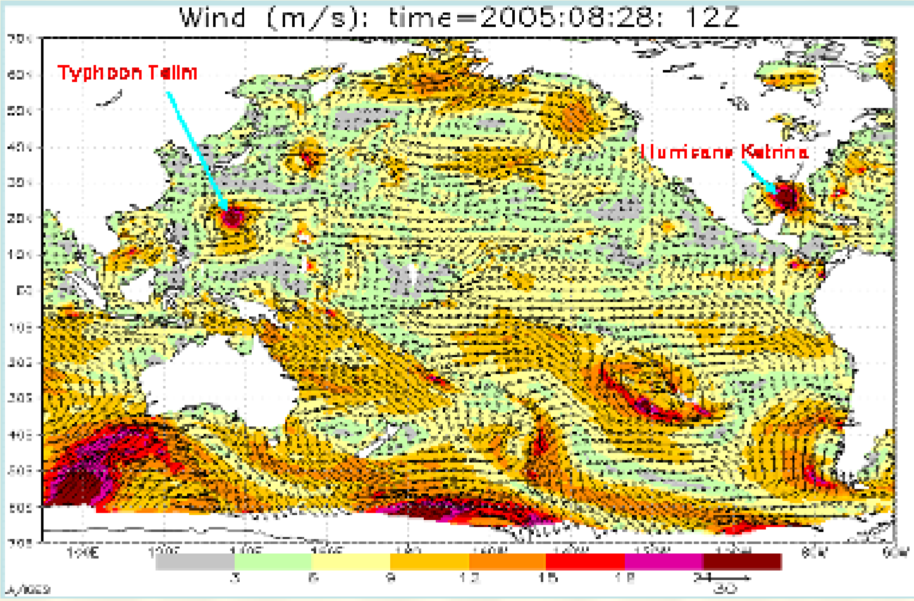

FIGURE 2: AN EXAMPLE OF THE BLENDED SEA WINDS AT 6-HOUR INTERVALS. NOTE THE SIMULTANEOUS TYPHOON TALIM AND HURRICANE KATRINA AT THIS PARTICULAR TIME.

Sea Surface Temperature (SST)

The widely used NOAA/Reynolds Optimum Interpolation (OI) SST analysis (e.g. Reynolds et al. 2004) has been improved with much higher resolutions (daily and 0.25°) and using multiple satellites (both infrared and microwave) and in-situ data. An advantage of the microwave observations (e.g., from AMSR-E) is that it can see through clouds, thus provide much more data coverage over clouded areas and time periods. The new versions (Reynolds et al. 2007) have the great improvements in terms of resolving ocean features such as the meandering of the Gulf Stream, the Agulhas Current, the equatorial jets, etc (Figure 3). In all the OI SST analyses, satellite biases are corrected with regard to the in-situ observations. The satellite bias corrections are important for climate studies and monitoring. An efficient and sufficient in-situ network has been designed (Zhang et al. 2006b) and has become operational as part the Global Ocean Observing System (GOOS).

Sea Surface Air Temperature and Humidity

The T_a and Q_a retrievals are based on measurements from the AMSU sounders onboard the NOAA series of satellites. The T_a retrieval uses AMSU-A data, while the Q_a retrieval uses both AMSU-A and AMSU-B observations. The Ta and Qa retrieval algorithms are developed using the neural network approach. The training datasets are constructed using co-located AMSU and buoy/ship data. The results show that the RMSE for T_a is 1.96°C against the ship data of Jackson et al (2006), and 2.22°C against selected buoy data (further quality control procedures will be applied to the next version to reduce the RMS). Additional SST constraints reduced the RMSE to ~ 0.94°C. However, one must note that the additional SST constraints reduce the potentially independent higher frequency variability of the air temperature. The RMS for the Q_a retrieval is 1.19 g/kg (Figure 4).

Data Access

More detailed data descriptions and accesses can be found through the links at the NCDC Website: http://www.ncdc.noaa.gov/oa/satellite.html, then click on your desired products. Most of the datasets are accessible by multiple methods, including ftp, OPeNDAP/TDS, and interactive graphic interface such as Live Access Server (LAS), from which one can do subsetting and downloading in one's desired formats (e.g., ascii/text, images, netCDF, IEEE binary, arcGIS, etc). Some direct links are:
ftp://eclipse.ncdc.noaa.gov/pub
http://eclipse.ncdc.noaa.gov:9090/thredds/catalog.html
http://nomads.ncdc.noaa.gov:8085/las/servlets/dataset.

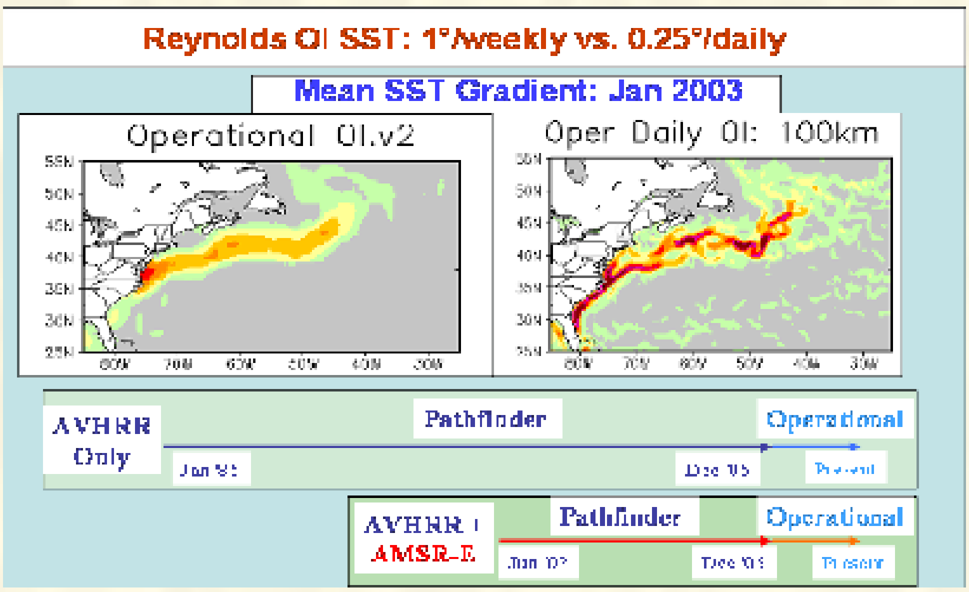

FIGURE 3. A COMPARISON OF THE OLD AND NEW REYNOLDS OI SST ANALYSES. SHOWN ARE THE SPATIAL SST GRADIENTS FOR JAN 2003. THE LEFT IS FOR THE OLD WEEKLY 1° OI SST (REYNOLDS ET AL. 2004); THE RIGHT IS FOR THE NEW DAILY 0.25° OI SST. THE BOTTOM PANELS SHOW THE TIMELINES OF THE AVAILABLE NEW OI SST ANALYSES.

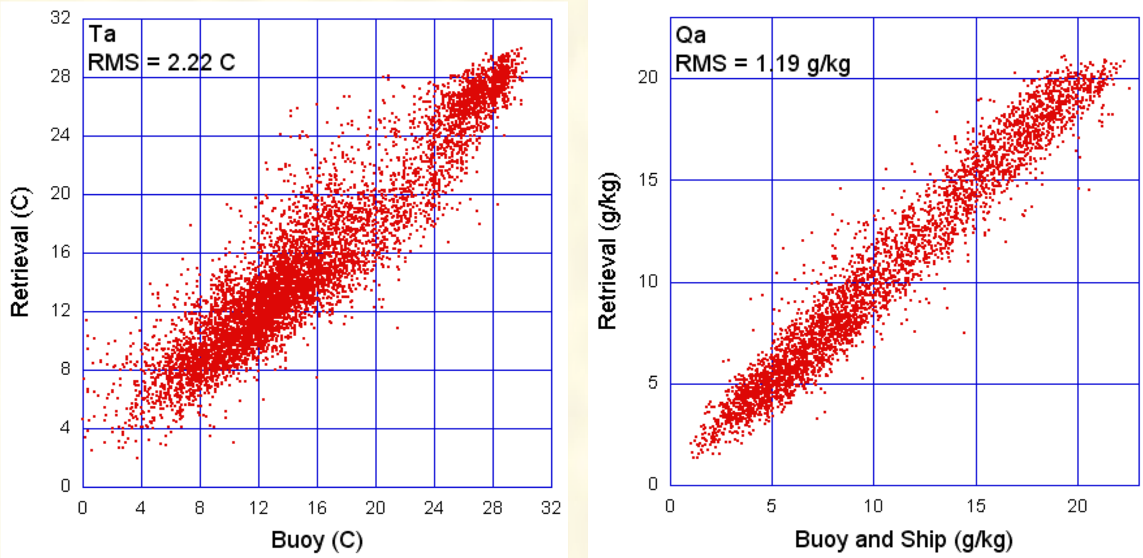

Figure 4. Evaluation of the retrieved T_a and Q_a against collocated ship and buoy data. Further quality control procedures will be applied to the next version to reduce the RMS in T_a.

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Improved Multi-Sensor Near-Surface Specific Humidity Satellite Retrieval

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The accuracy of satellite retrievals of air-sea turbulent heat fluxes has been largely limited by errors in near-surface specific humidity (Q_a) and temperature (T_a) observations. Satellite remote sensing of Q_a and Ta provides the opportunity to vastly improve global sampling thus providing opportunity to observe the global spatial distribution and variability of turbulent heat fluxes at the surface. The SeaFlux program (Curry et al., 2004) highlighted a need for higher resolution and smaller errors for Q_a and T_a observations to improve the overall accuracy of satellite-based turbulent heat flux retrievals from bulk formula. Satellite Q_a retrievals have mainly utilized the relationship between precipitable water and Q_a from SSM/I observations; however, the recent study by Jackson et al. (2006) introduced a new retrieval method combining microwave sounders (AMSU-A and SSM/T-2) with SSM/I that reduced RMS error relative to direct surface observations. Recent improvements to this multi-sensor approach were presented at the 4th SeaFlux Workshop that further reduced systematic and regional biases in the retrieval.

Improvements made to the Jackson et al. (2006) Q_a AMSU-A and SSM/I (AMA/MI) and SSM/I and SSM/T-2 (MI/T2) retrievals focused on reducing systematic and regional bias. The first update was to increase the total number of independent in situ/satellite matched observations to introduce a greater variety of atmospheric conditions in the training data set for the multivariate regression retrieval. This step reduced bias for retrievals for Q_a > 16 g/kg where the Jackson et al. (2006) retrieval tended to underestimate Q_a. Tropical and subtropical coverage has significantly improved by adding several additional cruises to the training data set for these regions. A second update was to change the multiple linear regression methodology to include a quadratic 52.8 GHz term for the AMA/MI Q_a retrieval

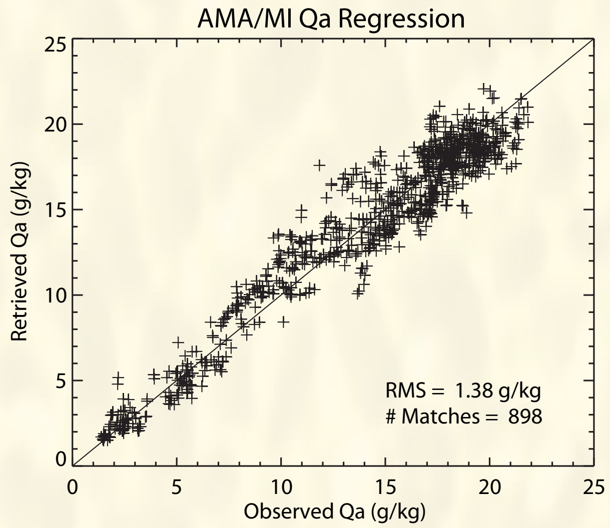

FIGURE 1. MULTI-SENSOR REGRESSION RESULTS FOR Q_A DATA.

and a logarithmic scaling of the satellite observations for the MI/T2 Q_a retrieval. Both transformations better linearized the relationship between the observed satellite brightness temperatures and Q_a. Figure 1 shows the regression results for the AMA/MI Q_a retrieval. RMS difference of 1.38 g/kg is substantially lower than the RMS of 1.78 g/kg obtained when only regressing the SSM/I observations. This result indicates the Qa retrieval benefits from using lower tropospheric temperature information provided by the AMSU-A 52 GHz channel. The improved MI/T2 retrieval algorithm resulted in an RMS difference of 1.50 g/kg indicating the SSM/T-2 vertical water vapor information also improves the Q_a retrieval though by a lesser degree than using AMSU-A. Formula for both retrievals can be acquired from our web site at www.esrl.noaa.gov/psd/psd2/coastal/satres/satflux.html.

ICOADS buoy and ship observations (Worley et al., 2005) were used for validation of the updated multi-sensor retrieval and for comparison with existing SSMI-only Q_a retrievals. Note that known biases in ICOADS data caused by differences in hygrometer type, instrument height, and day/night biases are currently being investigated but no corrections were applied in this comparison. Figure 2 gives a one month comparison in January 1999 of three SSM/I-only Q_a retrievals and the updated Jackson AMA/Mi Qa retrieval. The AMA/MI Q_a retrieval generally exhibits small bias relative to ICOADS for Q_a values between 2 g/kg and 20 g/kg. The Schulz Q_a (Schulz et al., 1995) is drier than ICOADS for $Q_a < 10$ g/kg, and Bentamy Q_a (Bentamy et al., 2003) is drier than ICOADS for Qa exceeding 15 g/kg. Q_a values below 2 g/kg and above 20 g/kg are not predicted well by any of the retrievals due to lack of satellite instrument sensitivity in those ranges. A July 1999 comparison with ICOADS in Figure 3a reveals a Q_a moist bias for all retrieval products in the North Pacific that correlates very well with regions exhibiting temperature inversions shown in Figure 3c. A seasonally-dependent static stability correction was developed using the difference between

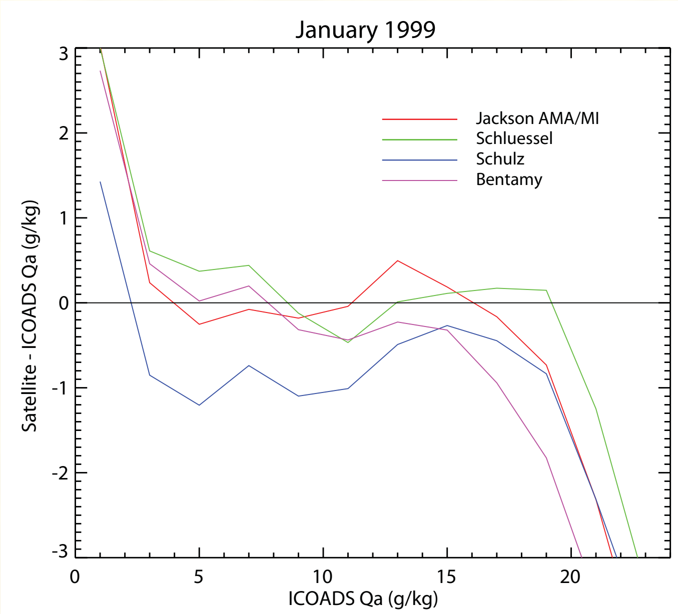

FIGURE 2. ICOADS Q_A JANUARY 1999 COMPARISON WITH UPDATED JACKSON AMA/MI, SCHLÜSSEL ET AL. (1995), SCHULZ ET AL. (1993), AND BENTAMY ET AL. (2003) RETRIEVALS. DIFFERENCES ARE BINNED BY 2 G/KG INTERVALS OF THE ICOADS REPORTED Q_A.

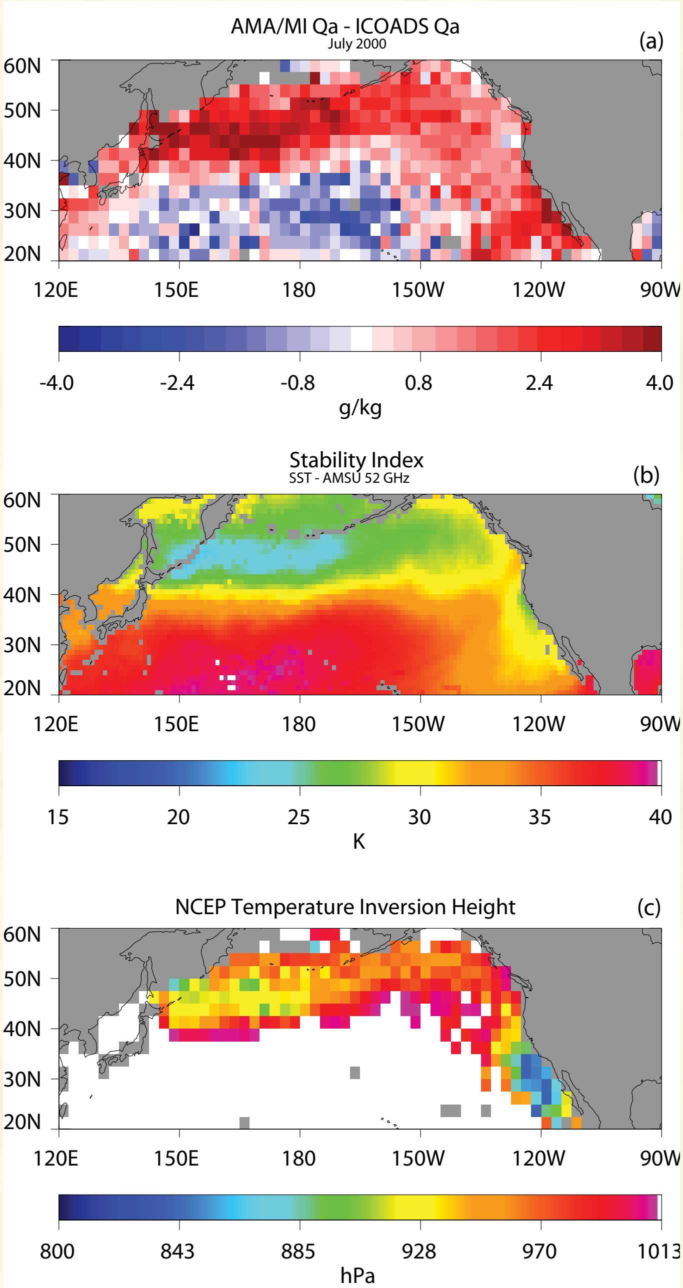

FIGURE 3. (A) JACKSON AMA/MI Q_A COMPARISON WITH ICOADS FOR JULY 2000 IN THE NORTH PACIFIC, (B) STABILITY INDEX PARAMETER DEFINED BY SST – AMSU 52 GHZ, AND (C) NCEP REANALYSIS MONTHLY-MEAN TEMPERATURE INVERSION HEIGHTS AND LOCATIONS.

sea surface temperature (SST) and AMSU-A 52 GHz channel (Figure 3b) to identify and correct this bias for the AMA/MI retrieval. The Q_a bias of 1.54 g/kg in Figure 3a is reduced to a bias of -0.15 g/kg following application of the correction.

A multi-year comparison between the ICOADS Q_a data and the HOAPS2 (Grassl et al., 2000), GSSTF2 (Chou et al., 2004), UCSB (Jones et al., 1999), Schlüssel (Schlüssel et al., 1995), and Jackson MI/T2 Q_a show regional biases are clearly largest for the tropical and subtropical regions. Figure 4 gives the Q_a average differences for the various methods over an 11-year period (1994-2004) except for HOAPS2 and GSSTF2 which have slightly shorter periods due to data availability. Schlüssel Q_a is wetter than ICOADS along the ITCZ and drier than ICOADS in the subtropical regions indicating that a cancellation of positive and negative bias contributes to the overall low Q_a bias for Q_a > 16 g/kg in Figure 2. The Schulz and Bentamy Q_a retrievals used in the GSSTF2 and HOAPS products respectively tend to be drier than ICOADS throughout most of the tropics and subtropics. The Jones Q_a used in the UCSB is generally wetter than ICOADS in the subtropical regions, but shows little bias in regions of high Q_a. The MI/T2 Q_a is generally drier than ICOADS in the tropics and subtropics but differences with ICOADS are generally smaller than for the other products. Midlatitude Q_a differences are smaller than tropical regions for most products except for GSSTF2 Q_a where Q_a is notably drier than ICOADS. Monthly mean Qa differences between these products can result in differences in monthly mean latent fluxes in subtropical high regions of up to 75 Wm^{-2}. Improving Q_a retrievals to address regional biases will reduce uncertainty in the latent heat flux data.

The Jackson Q_a and T_a retrieval formulas and data are available as 1.0 degree/daily and 0.5 degree/3-hourly grid products directly through our web site www.esrl.noaa.gov/psd/psd2/coastal/satres/satflux.html. Current plans are to have the MI/T2 retrieval available for the period 1993-2004 and the AMA/MI retrieval available for the period 1999-2007.

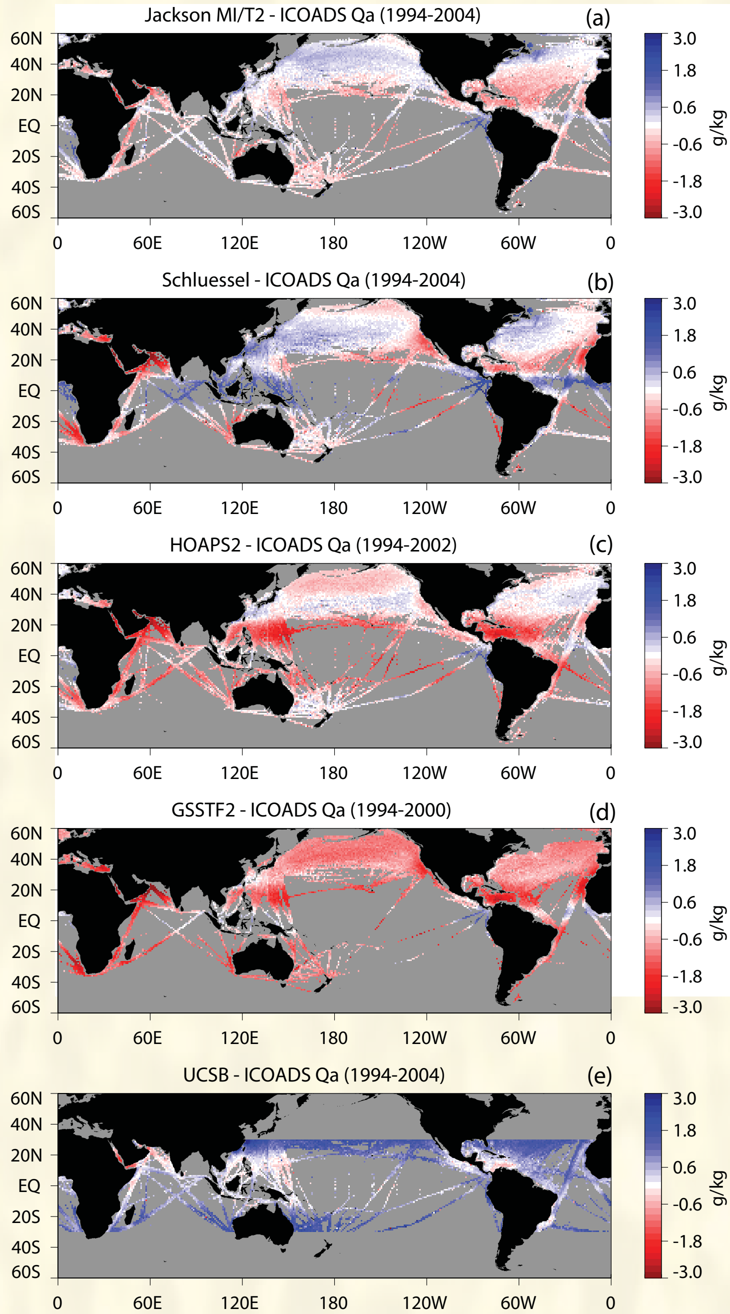

Figure 4. Multi-year comparison of ICOADS Q_a with (a) Jackson MI/T2 retrieval, (b) Schluessel et al. (1995) retrieval, (c) HOAPS2 Q_a product (derived using Bentamy et al. (2003)), (d) GSSTF2 Q_a product (derived using Schulz et al. (1993)), and (e) UCSB Q_a product (using Jones et al. (1999)).

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The HOAPS Climatology: Evaluation of Latent Heat Flux

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Introduction

Big advances in the investigation of the global ocean water cycle have been made by combined use of intercalibrated infrared and microwave satellite data in the last two decades. This largely broadens our knowledge of the detailed ocean atmosphere interaction by deriving high resolution products of precipitation, evaporation, and hence the resulting freshwater and energy fluxes. Such data also serve as a basic requirement for modelling of the global climate system by constraining the heat and freshwater transports at the ocean atmosphere interface (e.g. Flux News 4, Stammer) and the evaluation of the surface fluxes in coupled ocean atmosphere models. For the latent heat component of the water cycle at least five international groups exist that provide frequently updated remote sensing and in-situ data sets that can be compared to our HOAPS product. Intercomparisons of climatological means between these satellite-based data sets on global scale are presented in the following along with the corresponding zonal means. Also important is the temporal development of the latent heat parameter during the last 18 years between 1988 and 2005.

Data Products

HOAPS (Hamburg Ocean Atmosphere Parameters and fluxes from Satellite data) is a purely satellite based climatology of 15 global ocean water cycle parameters covering a time period from July 1987 to December 2005 (Andersson et al., 2007). HOAPS is based on brightness temperatures of the Special Sensor Microwave / Imager (SSM/I) and additionally uses NODC/RSMAS Pathfinder version 5 SST data. Inter-sensor calibration provides a homogeneous and reliable spatial and temporal coverage. The recent version HOAPS-3 is available in half degree gridded data of pentad and monthly means (HOAPS-G), twice daily data on a one degree grid (HOAPS-C) and SSM/I pixel-level resolution for each individual satellite (HOAPS-S). The results presented in this study are based on monthly mean HOAPS-G data. The latent heat product in units of W/m² is estimated using the bulk aerodynamic approach after Fairall (1996 and 2003).

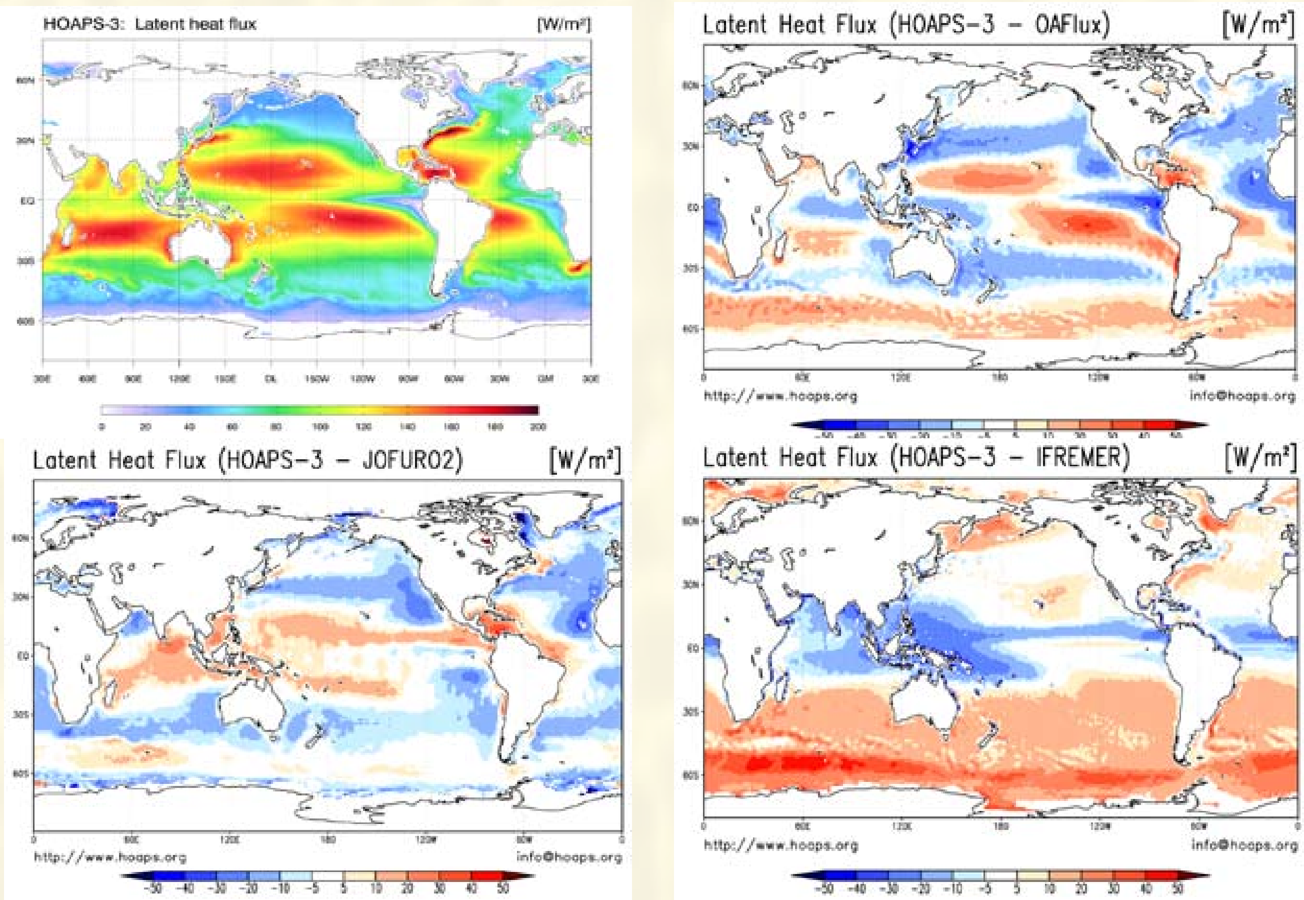

Figure 1: Climatological latent heat flux of HOAPS-3 between 1988 to 2005 (upper left panel) and difference plots for OAFlux (upper right), J-OFURO2 (lower left) and IFREMER (lower right) in W/m².

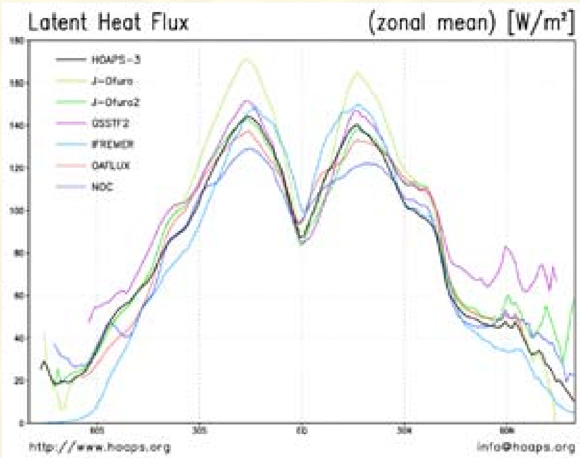

Figure 2: Zonal mean of the latent heat flux for various data sets compared to HOAPS-3 (thick black curve).

More detailed information on the HOAPS database and retrieval techniques have been presented in Flux Newsletter 4 and in Klepp et al. (2005). The data is freely available via www.hoaps.org.

HOAPS latent heat data is compared to four mainly satellite based climatologies and an in-situ data base. The Goddard Satellite based Surface Turbulent Fluxes data set (GSSTF2, Chou et al. 2003) provides turbulent flux products until 2001. The Objectively Analyzed air-sea FLUX climatology of WHOI (OAFLUX, Yu and Weller 2007) synthesizes satellite data, in-situ and NWP products until 2003. The Japanese Ocean Flux data set with the Use of Remote sensing Observations (J-OFURO; Kubota et al. 2002) derives turbulent heat fluxes from SSM/I and NWP data until 2006 in version 2. Bentamy et al. (2003) developed a remotely sensed data set of latent heat flux, named IFREMER in the following for the time period until 2006.

The National Oceanographic Centre (NOC) provides the Comprehensive Ocean Atmosphere Data Set (COADS, Josey et al. 1998) based on in-situ buoy and voluntary observing ship measurements. It is widely used as a reference for the evaluation of model and satellite based data sets until 1994.

Latent Heat Flux Evaluation

Figure 1 shows the HOAPS-3 climatological mean of the latent heat flux from 1988 to 2005 in W/m^2 compared to OAFlux, J-OFURO2 and IFREMER (1992 to 2005)

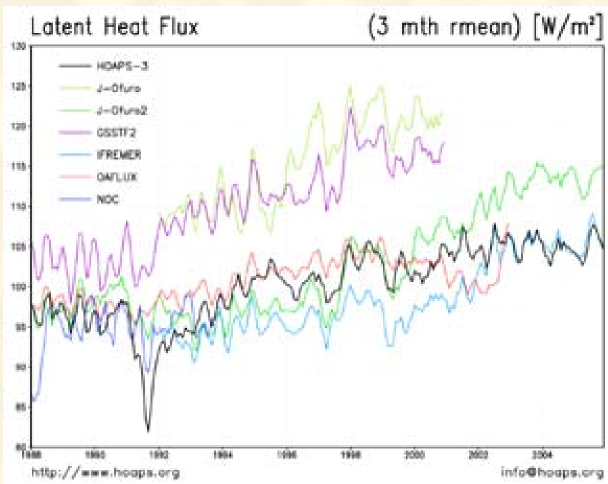

Figure 3: Temporal development of the latent heat flux given as a three month running mean between 1988 and 2005 for various data sets compared to HOAPS-3 (thick black curve).

as difference plots. High values (up to 180 W/m^2) occur in the 30°N to 30°S subtropic latitudinal band outside of the ITC. Largest values (up to 200 W/m^2) exist over the warm ocean currents of the Kuroshio and the Gulf Stream with a pronounced maximum during the cold season. Overall HOAPS-3 compares well against the data sets shown. The largest regional differences are in the order of 20%.Compared to OAFlux the HOAPS-3 maximum latent heat fluxes are higher in the subtropics while they are remarkably lower over the Gulf Stream and the Kuroshio current. Compared to J-OFURO2, HOAPS-3 shows higher latent heat flux values in the convective tropical regions and lower values in the extra-tropics. Compared to these findings IFREMER, however, exhibits an inverse latent heat flux pattern. Here, HOAPS-3 shows lower values in the tropics and higher values in the extra-tropics. Especially IFREMER has a systematic low bias in the Southern Oceans. The HOAPS-3 zonal mean of the climatological latent heat flux is shown in Figure 2 compared to both versions of J-OFURO, GSSTF2, IFREMER, OAFLUX and NOC. Here, each data set is used over its entire duration as can be seen in Figure 3. While most of the data sets are similar in the mid latitudes the differences become larger in the maxima of the subtropics. The temporal development of the latent heat flux for all data sets is given in Figure 3. The three month running mean is shown for the time period from 1988 to 2006. All satellite based data sets show a systematic increase in latent heat flux during the last 18 years. However, GSSTF2 and J-OFURO exhibit a positive bias that is no longer evident in J-OFURO2. As a refrerence, the in-situ based NOC data set is available between 1988 and 1994 and compares well to HOAPS-3 in terms of magnitude. The spike in the HOAPS-3 latent heat flux in mid 1991 is caused by a cool bias in the daily fields of the NODC/RSMAS Pathfinder SST due to undetected aerosol contamination during night-time measurements after the Mt. Pinatubo eruption (Reynolds 1993).

Conclusions

The HOAPS-3 climatology contains 15 parameters for global ocean water cycle and energy flux analysis for 18 complete years from 1987 to 2005. The data is freely available through www.hoaps.org.

Here, the evaluation of the latent heat flux shows that the HOAPS-3 climatology compares well against most of the state of the art satellite based data sets. Furthermore there is an overall agreement among these data sets that the latent heat flux has increased over the past two decades. The largest regional differences between the data sets usually stay below 20%.

Hence, the HOAPS-3 monthly and pentad means along with the scan based twice daily products are beneficial to assess the atmosphere ocean interface from space.

Acknowledgements

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MEDITERRANEAN REGIONAL ENERGY BALANCE

Surface Heat and Freshwater Fluxes into the Mediterranean Sea for the period 1985-2001

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1 Introduction

The semi-enclosed nature of the Mediterranean Sea makes it an attractive region to close heat and freshwater budgets. The first requirement is accurate measurements of the transports through Gibraltar and exchanges with the Black Sea. The latter have been found to be negligible for heat (Tolmazin, 1985). Estimates of the former are 5.2 ± 1.3 W/m^2 (Macdonald et al. 1994) and7±3 W/m^2 (Bethoux 1979) for heat and about 0.7m/yr (Bethoux and Gentili 1999) for freshwater, where the transports have been divided by the Mediterranean area of $2.5 \cdot 10^{12}$m^2 to give equivalent surface fluxes, Q_G and F_G respectively. Similarly, the frashwater from the Black Sea becomes F_B = 0.08m/yr.

The second requirement is estimates of the surface heat and freshwater fluxes. Bunker et al. (1982) and Garrett et al. (1993) closed the budget using rather ad hoc adjustments for biases in the wind and solar radiation respectively.

Finally, closure of the freshwater budget requires an estimate of the continental runoff R = 0.17 m/yr (Large and Yeager 2004) into the Mediterranean.

Castellari et al. (1998) developed a 'calibrated set' ofbulk formulas using the heat closure problem as a constraint. In this work we propose an alternative approach. Different corrections and adjustments are applied to the basic forcing fields required as inputs for our bulk formulas in order to resolve the 'Mediterranean heat closure problem'. In this way, we have computed the components of the surface heat and freshwater fluxes from 1985 through 2001. The purpose of this note is to describe the flux calculations (section 2), to demonstrate how the basin averaged fluxes, with the mentioned corrections, over the 17 years close theMediterranean heat and freshwater budgets (section 3), and to present the inter-annual variability on the considered period (section 4).

2 Data sets and methodology

The total heat flux, Q_T , and freshwater flux, F_T , are found as sums of components, and over timescales of negligible storage equal to the lateral Gibraltar transports:

$$Q_T = Q_S + Q_L + Q_H + Q_E \simeq -Q_B \simeq -6 \pm 2\mathrm{W/m^2} \quad (1)$$

$$F_T = P + E \simeq -(F_G + F_B + R) \simeq -0.95\mathrm{m/yr} \quad (2)$$

where all fluxes are considered positive into the Mediterranean. The radiative fluxes are the solar Q_S and long wave Q_L, while the turbulent fluxes are the sensible heat Q_H, the latent heat Q_E and the evaporation E, where Q_E and E are related by the latent heat of vaporization. P is the precipitation for which we used both ERA-40 (Uppala et al. 2005) and the Climate Prediction Center Merged Analysis of Precipitation (CMAP) (Xie and Phillip, 1996) data sets.

Basic fields provided by the ERA-40 reanalysis include

6-hourly zonal and meridional wind components, air and dew point temperatures, sea surface temperature (SST), mean sea level pressure and cloud cover.

High frequency surface fluxes have been computed from these fields, using bulk formulas (see Chiggiato et al. 2005) for a detailed description). However, the resulting fluxes are not useful, because the climatological averages fail to close the Mediterranean budgets with Q_T = 30 W/m^2 and F_T = 0.87 m/yr compared with the values given in (1) and (2) respectively.

3 Corrections and budget closure

Table 1 shows in each column the results for the heat and fresh water budgets obtained with the addition of the relative correction applied to the data set following the method suggested by Large and Yeager (2004).

	No Corr.	+Wind	+SST	+ISCCP-FD	+q specific
Q_S [W/m^2]	202	202	202	183	183
Q_L [W/m^2]	-87	-87	-88	-80	-80
Q_E [W/m^2]	-72	-94	-95	-95	-87
Q_H [W/m^2]	-13	-16	-18	-18	-18
Q_T [W/m^2]	30	5	1	-10	-2
E [m/yr]	-1.25	-1.62	-1.63	-1.63	-1.50
P [m/yr]	0.39	0.39	0.47	0.47	0.47
F_T [m/yr]	-0.87	-1.23	-1.16	-1.16	-1.03
P data set–>	Era-40	Era-40	CMAP	CMAP	CMAP

Table 1: Table of corrections/adjustments and relative results. The period considered ranges from 1985 to 2001

The biggest improvement on the total heat budget is obtained by means of the wind speed correction through comparison with satellite vectors winds from QSCAT (Chin et al. 1998). The ECMWF reanalysis seems to underestimate this field all over the basin, leading to too little evaporation (about 0.37 m/yr less) and latent cooling (22W/m^2). The second main effort is the use of the ISCCP-FD radiation data set for both the downward components of the radiation. The values computed with bulk formulas from Chiggiato et al. (2005), in fact, overestimate the real fields, and those bias are confirmed by comparison with local stations incoming solar radiation data (not shown). Other adjustments have been applied to the SST, using the optimal interpolated sea surface temperature (OI-SST) (Marullo et al. 2007), and to the computed specific humidity by the addition of an offset useful for the elimination of a low bias determined by comparison with NOC climatology (Josey et al. 1998).

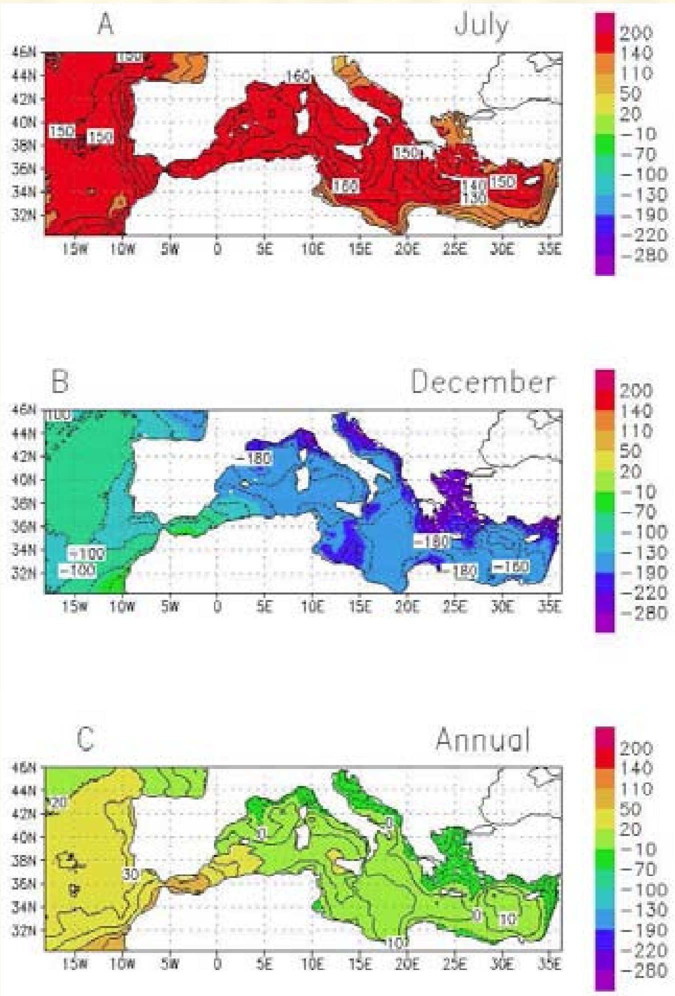

Figure 1: Climatology of QT [W/m2] for January (A), August (B) and annual (C).

Figure 1 shows the patterns of climatological values of Q_T for the month of July (A), December (B) and annual (C). The months represent the maximum heat gain heat loss respectively. The annual climatology presents a south-west to north-east gradient, with the areas of major heat loss located in the northern and Eastern coastal regions. The Alboran Sea, east of Gibraltar, is strongly heated because summer heating (A) is much larger that winter cooling (B) while the opposite behavior happens for the Aegean, Adriatic, Ligurian and Levantine basins.

4 Interannual variability

Figure 2 shows the inter-annual variability of Q_T and SST anomalies.

An approximation for the changes in heat fluxes directly due to SST changes is given by differentiating equation 1 with respect to SST:

$$\partial Q/(\partial SST) = -(5+4\,||\vec{V}||) \quad (3)$$

for |V | a characteristic wind speed in m/s.

Using |V | = 6.3 m/s for the Mediterranean, this coupling coefficient is about −30W/m^2/^{o}K. This value has been used for several years to correct the heat fluxes in basin scale general circulation modelling (Pinardi et al. 2003). Over most of the time series the negative correlation of eq. 3 holds, but over the last 5 years the coupling coefficient is only about −13 W/m^2/^{o}K, because the SST increase of ≃ 0.9^{o}C is accompanied by a warmer and more moist atmosphere (Figure 3). A similar coupling coefficientwas found by Doney et al. (1997) for the global ocean in a coupled climate model.

Of more interest are the changes taking place from

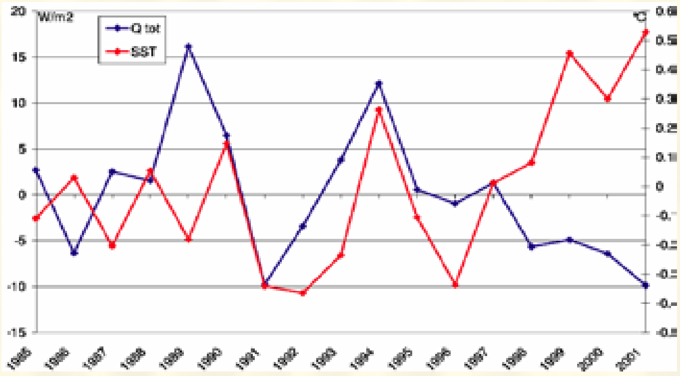

FIGURE 2: ANNUAL MEANS TIME SERIES FOR Q_T (BLUE LINE, LEFT AXIS) AND SST (RED LINE, RIGHT AXIS) ANOMALIES.

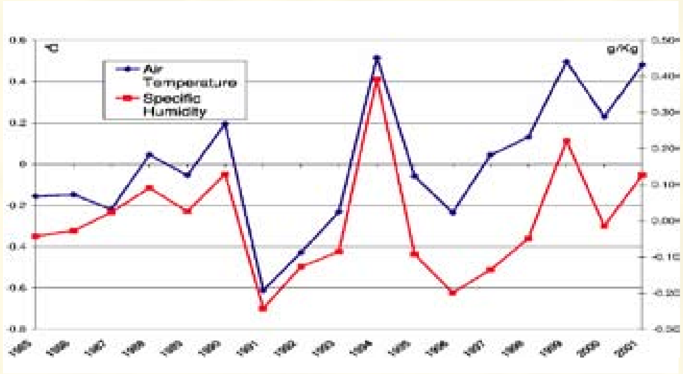

FIGURE 3: ANNUAL MEANS TIME SERIES FOR AIR TEMPERATURE (BLUE LINE, RIGHT AXIS) AND SPECIFIC HUMIDITY (RED LINE, LEFT AXIS) ANOMALIES.

1992 to 1994, when the increase of SST (0.6 °C) is less than the air temperature change (0.9 °C), which is accompanied by a very large increase in air humidity of (0.5 g/Kg). The implication in those atmospheric changes dominate to the point that Q_T also increase and the coupling coefficient becomes positive at about 25 W/m²/°K. The inter-annual variance of Q_T (Figure 2) makes it more difficult to close the Mediterranean heat budget with bigger accuracy. Both surface flux and transport measurements averages, would seem to require longer periods, and at least periodic significant heat storage is suggested by the positively correlated changes in SST and Q_T from 1990 to 1997. During those years, the increase of the surface solar radiation, which is the biggest term of eq. 1, is not followed by the same growth on the net longwave radiationwhich would be expected from the SST trend. The downward long wave component which is directly proportional to air temperature and water vapor pressure, becomes the most relevant part and able to dim the resultant net value. A confirmation of that is shown in picture 3: the anomaly taking place on the same period justify the mentioned hypothesis.

Acknowledgments

The OI-SST products used in this work were jointly produced by ENEA (Progetto Speciale Clima Globale) and Gruppo Oceanografia da Satellite (GOS) of the CNR - ISAC (Istituto di Scienze dell' Atmosfera e del Clima) as part of the EU project MFSTEP (EVK3-CT-2002-00075).

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NEW FLUX PRODUCT

A new 49-year global air-sea flux analysis from the WHOI OAFlux project

The Objectively Analyzed Air-sea Fluxes (OAFlux) project at the Woods Hole Oceanographic Institution announces the release of multidecade, global analysis for latent and sensible heat fluxes, 'ocean evaporation', and flux-related surface meteorological variables. Monthly, 1-degree gridded products are available online for the period 1958-2006, and daily gridded products are released for the satellite era 1985-2006. The data after 2006 will be updated in due course.

The OAFlux project is led by Drs. Lisan Yu (lyu@whoi.edu) and Bob Weller (rweller@whoi.edu) with the support from the NOAA Office of Climate Observation (OCO). Information about the OAFlux project, including products available, documentation, research, etc., can be found at the OAFlux web site: http://oaflux.whoi.edu. Please email the PIs for any comments on the OAFlux project and products.

PUBLICATIONS

New Surface Flux Papers

Michel, D., R. Philipona, C. Ruckstuhl, R. Vogt, and L. Vuilleumier, 2008: Performance and Uncertainty of CNR1 Net Radiometers during a One Year Field Comparison (to appear in J. Atmosph. Ocean. Tech.)

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FLUX CALENDAR

4 - 8 February 2008, The 3rd International TRMM Science Conference, Bally's Hotel, Las Vegas, NV, USA, http://www.harris.com/trmm/

13–18 April 2008, European Geosciences Union General Assembly 2008, Vienna, Austria. Special sessions AS2.01 Air-Land Interactions and AS2.02 Air-Sea Interactions, http://www.cosis.net/members/meetings/programme/view.php?m_id=49&p_id=296&PHPSESSID=b334a8c3223f4b2d727b190b8de87092

5 - 9 May 2008, The 4th IGBP Congress, Cape Town, South Africa, http://www.igbp2008.co.za/

6 - 9 May 2008, The 3rd JCOMM Workshop on Advances in Marine Climatology (CLIMAR-III), Gdynia, Poland, http://icoads.noaa.gov/climar3/

19 -23 May 2008, ICES-PICES-IOC Symposium on Effects of Climate Change on the World's Oceans, Gijón, Spain, http://www.pices.int/meetings/international_symposia/2008_symposia/Climate_change/climate_background_3.aspx

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