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Assessing Ocean and Atmosphere Analyses

by Michael Patterson, Interim Director

Over several decades, atmosphere and ocean model-based analyses have matured and proliferated, with climate modeling centers around the world generating routine real-time analyses as well as periodic retrospective reanalyses of the atmosphere and ocean state. These products support a range of scientific investigations, from initializing climate and Earth system model simulations, predictions, and projections to identifying and tracking the evolution of modes of variability, elucidating trends and extremes in the atmosphere and ocean, and providing a basis for decision support analyses, among a variety of other applications.

Progress in development and assessment of ocean and atmosphere analyses products was reviewed at two workshops held in conjunction last November. The "Evaluation of Reanalyses – Developing an Integrated Earth System Analysis (IESA) Capability Workshop," surveyed data assimilation-based analyses efforts across the spectrum of Earth system component and coupled models, explored the quality and limitations of assimilation approaches and analyses products, and identified pathways for future improvements. The "3rd

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IN THIS ISSUE

Driving Ecosystem and Biogeochemical Models with Optimal State Estimates of the Ocean Circulation

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The ocean plays a key role in the cycling of carbon through the earth system. There is a continuous flux of carbon dioxide with the atmosphere driven by the physical circulation of the ocean and by the uptake of carbon by photosynthesizing organisms (phytoplankton) in the surface ocean. Phytoplankton are responsible for about half the primary production of the earth biosphere and form the base of the marine food web. A portion of the carbon they fix in the surface waters is transported ("exported") to the deep ocean. Currently the ocean is a sink of carbon, taking up about one third of anthropogenic carbon dioxide. How does physical variability, and will future changes, affect the ocean's ability to take up carbon? How will a warmer ocean affect the marine primary producers?

Marine biogeochemical models have been developed to understand the controls and variations in the distribution of chemical elements (e.g. carbon, nitrogen, iron) in the ocean. Ecosystem models attempt to understand the structure and function of the marine food web; community structure impacts biogeochemical cycles including export of carbon to the deep ocean. The Ocean Carbon Model Intercomparison Project (OCMIP) highlighted the large sensitivity of results, such as export of carbon, to the physical circulation of the models (Doney et al., 2004; Najjar et al., 2007). Unrealistic physical environments will render the biogeochemical results inadequate to answer some fundamental questions. Biogeochemical and ecosystem models have been increasing in sophistication over the last few decades (Six and Maier-Reimer, 1996; Moore et al, 2002; Le Quéré et al, 2005; Follows et al, 2007), but the need for good physical circulation to drive them remains a crucial mandate.

Ocean state estimation is a least-squares fit of a numerical general circulation model to a variety of observations, including global satellite and scattered in situ ocean data, providing the best possible estimates of the ocean circulation. The methods used to reduce the misfit between model and data vary, ranging from sequential/filter methods such as optimal interpolation or Kalman filters, to variational/smoother methods such as the adjoint or Lagrange multiplier method or the Green's function method (Wunsch, 1996; Talagrand, 1997). The ocean state estimate products typically include time-varying flow fields, temperature, salinity, and mixing. Many data assimilation groups have made these products freely available (see the OceanObs'09 Community White Paper by Lee et al. (2010) for a detailed list). These improved fields of the physical state of the ocean are valuable for ocean biogeochemistry models.

The Estimating the Circulation and Climate of the Oceans (ECCO) consortium (Wunsch et al, 2010) has developed several products that have been used for biogeochemical and ecosystem

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Atmospheric Circulation Reconstructions over the Earth (ACRE) Workshop" examined the use of historical instrumental records and reanalyses, and reviewed efforts to facilitate improved accessibility and utility of the datasets. An overview of topics covered and recommendations is provided herein.

Also featured in this issue of Variations are two papers highlighting research presented at the IESA Workshop. Dr. Stephanie Dutkiewicz (MIT) summarizes physical and biogeochemistry ocean modeling of the ocean state and suggests specific ocean assimilation metrics to constrain both physical ocean circulation and biogeochemistry modeling.

Xue et al. evaluate upper ocean heat content from eight model analyses based on ocean data assimilation systems and two objective analyses based on in situ observations. The authors present time series and trend analyses demonstrating the reliability of ocean analysis in estimating heat content variability and their use in monitoring climate signals.

Recommendations from the reanalyses workshops will be considered at the U.S. CLIVAR Summit this July in Woods Hole, MA. The first day of the Summit will co-convene with the Ocean Carbon and Biogeochemistry Summer Workshop to explore collaboration on intersecting research interests including modeling issues raised in Dr. Dutkiewicz' article and a full range of integrated observation and data needs, coupled process understanding, and prediction and impacts research.

Variations

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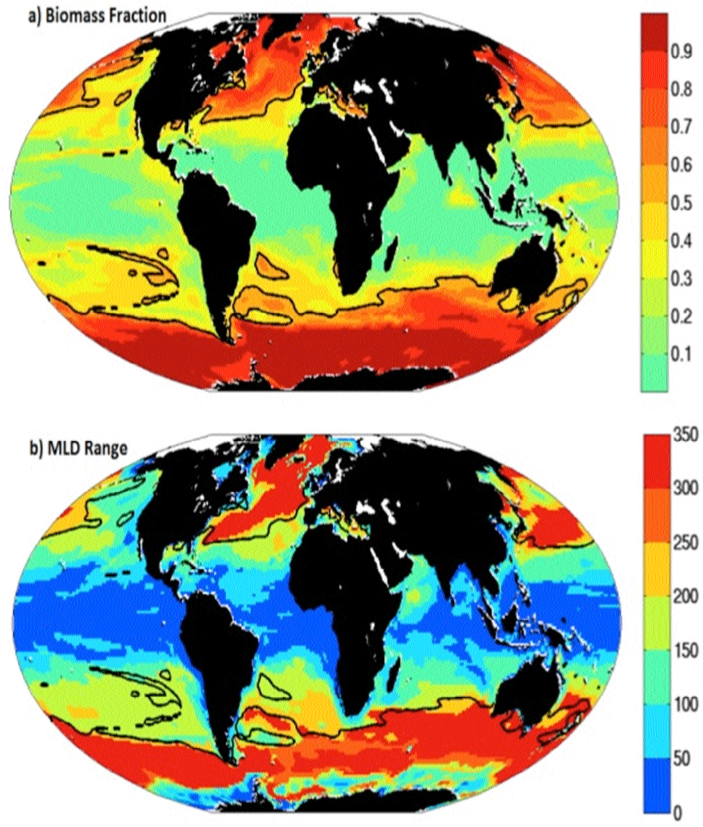

Figure 1. Output from the ECCO-GODAE state estimate (Heimbach and Wunsch, 2007) drive an ecosystem model with self-assembling community structure. (a) Fraction of total phytoplankton biomass made up of large, opportunistic species. (b) Relative regional stability shown by annual range of mixed layer depth (m). Contour indicates where half the biomass are opportunists. Opportunistic species, with quick growth rates, dominate where the water column is less stable. Slower growing phytoplankton whose small size makes them better at nutrient acquisition dominate in the more stable environments. (Figure modified from Dutkiewicz et al., 2009)

applications. ECCO -GODAE state estimates using the adjoint method, at 1^{o} resolution (Heimbach and Wunsch, 2007), have provided a strong physical background for the development of the ocean ecosystem and biogeochemistry model of Follows et al., (2007). The estimates of the physical ocean state transport the biogeochemical tracers (such as nutrients, organic matter) and many phytoplankton types. The biogeochemical and biological tracers interact through the formation, transformation and remineralization of organic matter.

Circulation and mixing controls the rate of vertical and horizontal supply of nutrients to the surface ocean. Mixing within the water column determines the amount of light to which phytoplankton are exposed. The many different phytoplankton types have growth characteristic that are randomly assigned from ranges suggested by laboratory studies, with some simple imposed trait trade-offs. The chemical and physical environments in the ocean model set which types and combinations of phytoplankton survive in any region (e.g. Follows et al., 2007; Dutkiewicz et al., 2009; Monteiro et al., 2011). For instance, trade-offs in growth strategies lead to large fast growing opportunists dominating the communities in regions of high seasonal disturbances, while strategies for efficient uptake of scarce resources are more useful in stable environments (Fig. 1, Dutkiewicz et al., 2009). The physical environment has a strong control not only on the emergent communities, but also has a role in setting the patterns of biodiversity of phytoplankton. A poleward decline in biodiversity can be explained by the relative stability of the environment (Barton et al. 2010); overlain are regional "hotspots" of high diversity (Fig. 2). These patterns are captured in a simulation where the ecosystem model is driven by the ECCO2 global eddy-permitting general circulation model, which uses a Green's function method to partially adjusted the model to observations (Menemenlis et al., 2008). Enhanced biodiversity is seen in western boundary current regions where different water masses, with disparate communities of phytoplankton, are mixed together.

Biological processes lead to a constant downward flux of elements, such as carbon, to the deep ocean. Physical processes bring these elements back up from the deep and redistribute them horizontally, particularly in mode waters (see e.g. Sarmineto et al., 2004). Carbon dioxide enters the ocean from the atmosphere in some regions and is expelled in others, driven largely by temperature differences in those surface waters. Biogeochemical models can explore the processes that are most relevant for these redistributions of carbon. Regional eddy-permitting (1/6°) adjoint-based state estimates of the Southern Ocean (SOSE, Mazloff et al., 2010) have helped elucidate the crucial role of Ekman transport (Ito et al., 2010), especially in relation to anthropogenic carbon. In the Southern Ocean most of the anthropogenic carbon uptake occurs near the Antarctic polar front. However, the column inventory of this carbon is largest further equatorward (Fig. 3) . Though locally the anthropogenic carbon is advected away from the uptake sites by mesoscale eddies, it is the wind driven Ekman transport that leads to the cross frontal redistribution. Time scales are important in these processes, and adequate capture of the Ekman processes are essential in obtaining such results.

Biogeochemical models require accurate and dynamically consistent ocean circulation fields. This is often in contrast to other applications, especially in forecasting, where "re-analysis" produces optimal initial conditions of temperature and salinity at discrete intervals, but which do not require budget closure between any two "analysis" steps. Such imbalances can cause inaccurate circulation, especially vertical velocities, causing spurious adjustments to biogeochemical fields. However, the use of estimates based on variational/smoother methods (e.g. Fukumori, 2002) can minimize these inconsistencies (McKinley, 2002). Some physical metric may be relatively more important to biogeochemical models than other applications using physical state estimation products. Mixed layers play a key role in determining the light environment of phytoplankton growth, and the rate of water mass formation plays a key role in redistributing carbon and nutrients. A stronger emphasis on these metrics in the assimilations could improve physical general circulation models in a manner useful for biogeochemical applications.

Data assimilation remains relatively new in ocean biogeochemistry itself. However, the expanding satellite ocean colour and biogeochemically relevant in situ observations are leading to increased use of these techniques (see Gregg et al., 2009 for a list of studies). Global models assimilating satellite derived chlorophyll suggest the utility of these approaches (e.g. Gregg 2008; Tjiputra et al., 2007). In most of these studies, the physical circulation remains unconstrained. Since biogeochemical model results are sensitive to the model physical circulation, marine biogeochemical metrics could be key in improving the modeling of physical processes (Najjar et al., 2007). Including Chlorofluorocarbon (CFC) and radiocarbon observations to constrain deep and bottom water transport rates and pathways in a global (though time-invariant) model, has important implications for the strength of the overturning circulation (Schlitzer, 2005). As ocean biogeochemical models rise to meet the challenge of quantifying air-sea fluxes of carbon dioxide in a changing world, it is likely that simultaneous assimilation of physical and biogeochemical observations will be of greater value.

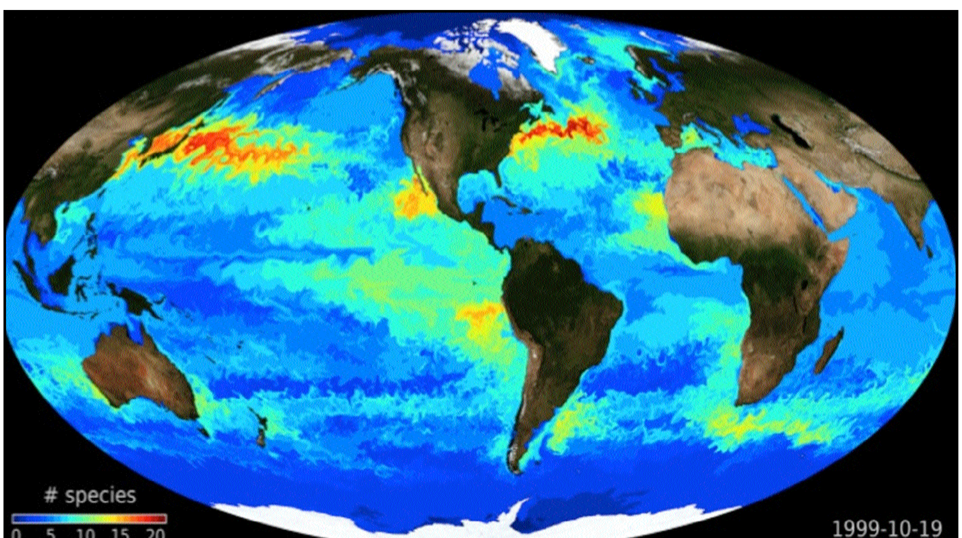

Figure 2. Output from the ECCO2 state estimate (Menemenlis et al., 2008) drive the ecosystem model with many phytoplankton types. Biodiversity of phytoplankton, defined here as number of species with biomass above a threshold value, shows distinct global patterns. A poleward reduction in diversity is linked to the amount of disturbances to the environment (Barton et al., 2010). Hot spots of diversity in western boundary currents and other regions of energetic circulation show the importance of mixing of different water masses. Simulation performed by Oliver Jahn and Chris Hill at MIT. (Figure credit: Oliver Jahn)

Acknowledgments

The author would like to thank Patrick Heimbach and Ichiro Fukumori for comments and suggestions, which greatly improved this article. Taka Ito and Oliver Jahn kindly provided figures.

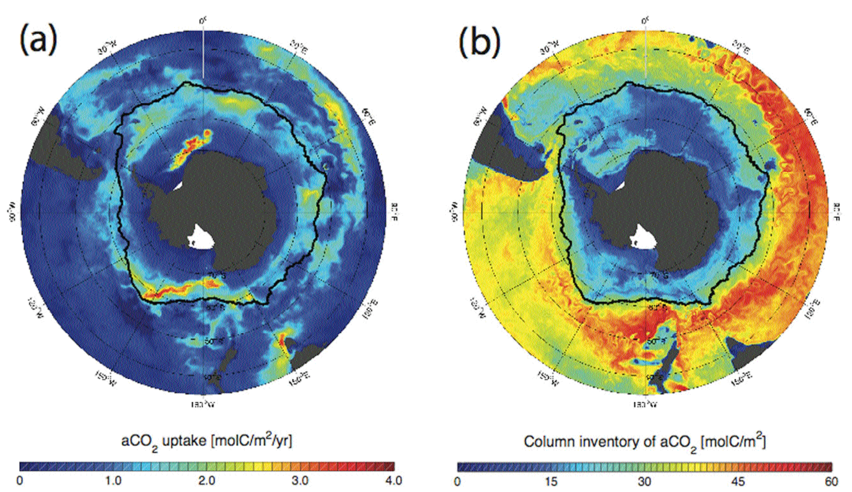

Figure 3. Output from the Southern Ocean State Estimate (SOSE, Mazloff et al., 2010) drive a model of anthropogenic carbon. (a) 2 year average of uptake of anthropogenic carbon dioxide; (b) column inventory of anthropogenic carbon after 2 years of simulation. Black line indicates the location of the Antarctic Polar Front. Ekman transport is crucial in redistributing the anthropogenic carbon equatorward. (Figure from Ito et al., 2010 with permission of the authors).

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Evaluation of Reanalyses – Developing an Integrated Earth System Analysis (IESA) Capability Workshop and the 3rd Atmospheric Circulation Reconstructions over the Earth (ACRE) Workshop: Reanalysis and Applications 1-5 November 2010, Baltimore, MD

by: David M. Legler[1], Randall Dole[2], Rob Allan[3], Gil Compo[4], and Jim Carton[5]
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Evaluation of Reanalyses – Developing an Integrated Earth System Analysis (IESA) Capability

Understanding how earth system components and their interactions are changing over time is crucial to developing national strategies for managing climate risk. Despite vast improvements in observational capabilities, observations alone are, and will continue to be, insufficient to fully determine the present state of the atmosphere, much less quantify the states of other components of the earth system such as the ocean, land surface, cryosphere and biosphere. Thus, a fundamental scientific challenge remains to obtain optimal estimates of past and present climate and, more generally, of the full earth system, in order to determine how and why changes are occurring and to assess the associated impacts.

Progress and next steps toward achieving this scientific grand challenge were addressed at the Evaluation of Reanalyses – Developing an Integrated Earth System Analysis (IESA) Capability Workshop, organized by US CLIVAR (see http://www.usclivar.org/Reanalysis2010.php). Over 90 participants focused on strengths and limitations of recent U.S. reanalyses and identifying areas where improvements could be made; demonstrating scientific and practical applications of current products; and developing goals of future efforts leading to an integrated Earth system analysis (IESA) capability.

The past decade has witnessed remarkable advances in atmospheric and ocean reanalyses. There are now multiple streams of reanalyses addressing varying needs. The resolution and quality of reanalyses have improved remarkably, substantially increasing their value for research and applications. Presentations identified challenges and opportunities, both nationally and internationally, including strengthening collaborations to develop and improve access to observational data sets and reduce observational biases.

Emerging developments were described in analyses of components of the earth system beyond the physical atmosphere (e.g., atmospheric chemical constituents, land surface, cryosphere, and biosphere, including ocean biogeochemistry and the carbon cycle), and in fully coupled data assimilation (e.g. between ocean and atmosphere) to provide more internally consistent estimates of interactions among system components. Existing and emerging applications (e.g., in renewable energy) were described. Significant improvements were noted for some uses, but other areas such as interfacial fluxes continue to have major deficiencies. Characterizing and communicating uncertainty of reanalyses remains as a key challenge. Participants agreed that multiple streams of efforts will be required to address the broad range of scientific and practical needs and to improve analyses of individual components.

Progress toward an IESA will proceed in steps. To achieve the highest quality, it will be crucial to develop and support coordinated and sustained efforts in reanalyses both nationally and internationally. Near-term emphases should be on evaluating and improving reanalysis products for GCOS Essential Climate Variables and developing and reprocessing observational data to reduce biases. Advances appear feasible in several areas having high relevance to policy and decision support, including addition of atmospheric constituents, the carbon cycle, and coupling of system components that may lead to accelerated (or diminished) rates of climate change. This workshop served as an important step in bringing together scientists from many traditionally separate disciplines in geophysical and biological sciences to begin to develop a more accurate and internally consistent record of how the earth system is changing over time.

3rd Atmospheric Circulation Reconstructions over the Earth (ACRE) Workshop: Reanalysis and Applications

The 3rd ACRE workshiop was held in Baltimore, MD and overlapped and interlinked, with the Evaluation of Reanalyses – Developing an Integrated Earth System Analysis (IESA) Capability meeting mentioned above.

Previous ACRE workshops of this kind were held in Zurich in 2008, with the 1st ACRE Workshop: Reanalyses

Data, Historical Reanalyses and Climate Applications, and in 2009, with the 2nd ACRE Workshop: Shaping an ongoing road map for ACRE at Lamington National Park in Queensland, Australia. Reports and individual presentations from these meetings can be found at: http://www.met-acre.org/meetings-and-workshops-1.

ACRE (http://www.met-acre.org/) undertakes and facilitates the recovery of instrumental terrestrial and marine global surface weather observations to underpin global weather reconstructions and reanalyses spanning the last 200-250 years (http://reanalyses.org) for the full range of international climate and weather user needs.

The initiative links together more than 35 international scientific projects, institutions and organisations. Its activities have been endorsed by the WMO Commission for Climatology, the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update), the JCOMM Expert Team on Marine Climatology and the World Climate Research Programme.

The goal of the major ACRE Workshop for 2010 was to shape the efficient use of the historical weather data and reanalysis products ACRE is both producing and facilitating with its international partners (https://sites.google.com/a/met-acre.org/acre/Home/ACRE_G2.png?attredirects=0). Thus, this workshop brought together the main ACRE partners who have been working to use the historical weather reanalyses being produced by NOAA and CIRES for the full range of users – from climate researchers and the diverse climate applications community to educators and students. The applications and user communities initiated the call for an initiative like ACRE, and thus it is critical that ACRE addresses the provision of useful results that can be easily and readily applied worldwide - it is a key test in measuring ACRE's success.

The 3rd international ACRE workshop highlighted the broad array of uses of ACRE-facilitated datasets: the International Surface Pressure Databank (http://dss.ucar.edu/datasets/ds132.0/), the International Comprehensive Ocean Atmosphere Data Set (ICOADS, http://icoads.noaa.gov/), and the 20th Century Reanalysis (20CR, http://www.esrl.noaa.gov/psd/data/20thC_Rean/). These were used to study variations in El Niño-Southern Oscillation, storminess, drought, seasonal rainfall, tornado outbreaks, hurricanes, and many other applications. Considerable science in the areas of weather and climate extremes, climate analysis, and climate trends was also presented.

The workshop also provided a venue for ACRE outreach and where preliminary results in the areas of citizen science, massive scale data handling and web-based, state-of-the-art high-resolution visualisations of the data and reanalyses products could be addressed. The successful development of this technology is crucial to making the full impact of the output and outreach from the international ACRE initiative as user friendly, tailored and shaped as is possible. Workshop presentations are available at and a full report can be found at http://www.joss.ucar.edu/events/2010/acre/agenda.html and http://www.met-acre.org/meetings-and-workshops-1/3rdACRE Workshop.doc?attredirects=0.

As a result of this workshop, an ACRE inclusion was accepted at the UNFCCC CoP16 meeting in Cancun, Mexico in 2010 by the Subsidiary Body for Scientific and Technological Advice (SBSTA) on 'Research and Systematic Observation': 'The SBSTA further noted the importance of historical observations as the basis for analysis and reanalysis and encouraged Parties and relevant organizations to increase their data rescue and digitization of historical observations and to establish and strengthen international coordination initiatives for these activities.'

U.S. CLIVAR Welcomes New Panel Members

Predictability, Predictions and Applications Interface Panel
Arun Kumar, NOAA NCEP, co-chair
Annalisa Bracco, Ga. Tech, co-chair
Curtis Deutsch, UCLA
Xiouhua Fu, University of Hawaii
Gregg Garfin, University of Arizona
Richard Grotjahn, UC Davis
Ron Lindsay, University of Washington
Cristiana Stan, COLA
Liqiang Sun, IRI
Gabriel Vecchi, NOAA GFDL

Process Studies Model Improvement Panel
Joao Teixeira, NASA JPL, co-chair
Rob Wood, University of Washington, co-chair
Lisa Beal, University of Miami - RSMAS
Baylor Rox-Kemper, University of Colorado
Michael Gregg, University of Washington
Meibing Jin, University of Alaska, Fairbanks
Igor Kamenkovich, University of Miami - RSMAS
David Lawrence, NCAR
Joel Norris, UCSD
Joellen Russell, University of Arizona
Sukyoung Lee, Pennsylvania State University

Phenomena, Observations and Synthesis Panel
Nick Bond, University of Washington, co-chair
Michael Bosilovich, NASA GSFC, co-chair
Mathew Barlow, University of Massachusetts, Lowell
Antonietta Capotondi, NOAA CIRES
Simon de Szoeke, Oregon State University
Benjamin Giese, Texas A&M
Sasha Gershunov, UCSD
Rick Lumpkin, NOAA AOML
Dimitris Menemenlis, NASA JPL
Yan Xue, NOAA NCEP
Rong Zhang, NOAA GFDL

U.S. CLIVAR thanks the members rotating off for their contributions and community service: Frank Bryan, Kathy Donohue, Sirpa Hakkinen, Tony Lee, Chris Meinen, Ed Schneider, Dan Vimont, Wanqiu Wang, Ning Zeng, and Paquita Zuidema

Comparative Analysis of Upper Ocean Heat Content Variability from Ensemble Operational Ocean Analyses

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[4]Mercator-Océan, [5]Met Office Hadley Centre, [6]Japan Meteorological Agency,
[7]NASA/GSFC/GMAO, [8]NOAA/GFDL, [9]Centre for Australian Weather and Climate Research (CAWCR)

Upper ocean heat content (HC) is one of the key indicators of climate variability on many time-scales extending from seasonal to interannual to long-term climate trends. For example, HC in the tropical Pacific provides information on thermocline anomalies that is critical for the long-lead forecast skill of ENSO. Since HC variability is also associated with SST variability, a better understanding and monitoring of HC variability can help us understand and forecast SST variability associated with ENSO and other modes such as Indian Ocean Dipole (IOD), Pacific Decadal Oscillation (PDO), Tropical Atlantic Variability (TAV) and Atlantic Multidecadal Oscillation (AMO). An accurate ocean initialization of HC anomalies in coupled climate models could also contribute to skill in decadal climate prediction.

Errors, and/or uncertainties, in the estimation of HC variability can be affected by many factors including uncertainties in surface forcings, ocean model biases, and deficiencies in data assimilation schemes. Changes in observing systems can also leave an imprint on the estimated variability. The availability of multiple operational ocean analyses (ORA) that are routinely produced by operational and research centers around the world provides an opportunity to assess uncertainties in HC analyses, to help identify gaps in observing systems as they impact the quality of ORAs and therefore climate model forecasts. A comparison of ORAs also gives an opportunity to identify deficiencies in data assimilation schemes, and can be used as a basis for development of real-time multi-model ensemble HC monitoring products.

The OceanObs09 Conference called for an intercomparison of ORAs and use of ORAs for global ocean monitoring (Xue et al., 2010a). As a follow up, we intercompared HC variations from ten ORAs – two objective analyses based on in-situ data only and eight model analyses based on ocean data assimilation systems. The mean, annual cycle, interannual variability and long-term trend of HC have been analyzed.

Operational ocean analyses

National Centers for Environmental Prediction (NCEP), NOAA/USA

The NCEP produces ORA using the Global Ocean Data Assimilation System (GODAS) (Behringer and Xue, 2004). The GODAS is based on the Geophysical Fluid Dynamics Laboratory's Modular Ocean Model version 3 (MOM3) at 1° with 1/3° equatorial refinement, 40 levels and a 3D variation scheme. Observed temperature and synthetic salinity profiles and observed SST are assimilated daily. A suite of comprehensive global ocean monitoring products has been derived with GODAS (http:// www.cpc.ncep.noaa.gov/products/GODAS). Recently, a new reanalysis for the atmosphere, ocean, sea ice and land over 1979-2009 has been completed as the Climate Forecast System Reanalysis (CFSR). The oceanic component of CFSR includes many advances: (a) the MOM4 ocean model with interactive sea-ice, (b) a 6 hour coupled model forecast as the first guess, (c) inclusion of the mean climatological river runoff, and (d) high spatial (0.5° by 0.5°) and temporal (hourly) model output (Xue et al., 2010b).

Geophysical Fluid Dynamics Laboratory (GFDL), NOAA/USA

The GFDL assimilation system consists of an Ensemble Kalman Filter applied to GFDL's second generation fully coupled climate model CM2.1, (Zhang et al., 2007). The ocean component of the ensemble coupled data assimilation (ECDA) is configured with 50 vertical levels (22 levels of 10-m thickness each in the top 220 m) and 1° horizontal B-grid resolution, telescoping to 1/3° meridional spacing by 1° near the equator. The atmospheric component has a resolution of 2.5° x 2° with 25 vertical levels. The system is fully coupled, assimilating both atmosphere and ocean observations contemporaneously building covariances between the component models fluxes. Observed temperature and salinity profiles and SST are assimilated daily on the ocean side. The GFDL reanalysis covers the period 1970 to present and is updated monthly (http://www.gfdl.noaa.gov/ocean-data-assimilation).

Global Modeling and Assimilation Office (GMAO), NASA/USA

The GMAO reanalysis uses the GEOS-5 coupled atmosphere-ocean general circulation model which is based on MOM4 (0.5° with 1/4° equatorial refinement and 40 levels) and the GEOS-5 AGCM (1° x 1.25° with 72 levels) model. The atmosphere is constrained by the atmospheric fields from the Modern Era Retrospective Analysis for Research and Applications

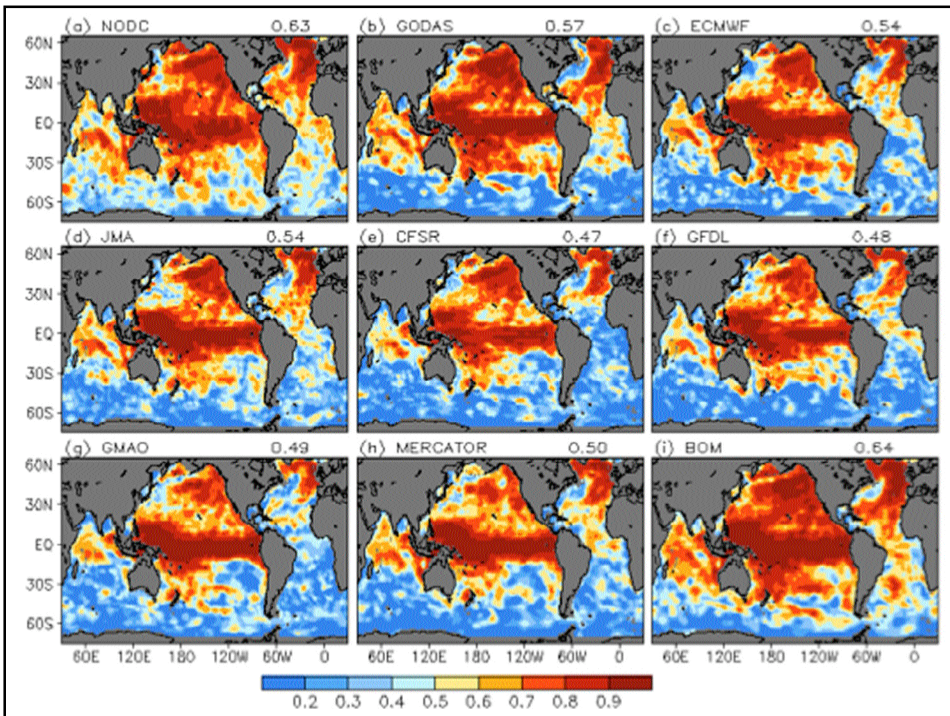

Figure 1. Anomaly correlation with EN3 in 1985-2009 for (a) NODC, (b) GODAS, (c) ECMWF, (d) JMA, (e) CFSR, (f) GFDL, (g) GMAO, (h) MERCATOR, and (i) BOM. The average of correlation over the global ocean is shown on the right top of each figure.

(MERRA) (Rienecker et al., 2011). The ocean data assimilation uses a multivariate ensemble optimal interpolation (EnOI) to infer background-error covariances from a static ensemble of 50 model state-vector EOFs. Observed temperature and salinity profiles and observed SST are assimilated daily. The XBT temperature profiles have been corrected according to Levitus et al., 2009. The climatological sea surface salinity is also assimilated to compensate for errors in fresh water input from precipitation and river runoff.

European Centre for Medium-Range Weather Forecasts (ECMWF)

The ECMWF ocean reanalysis, referred to as ORA-S3, has been operational since August 2006, providing ocean initial conditions for the ECMWF seasonal and monthly forecasts since March 2007. The ORA-S3 is based on the Hamburg Ocean Primitive Equation (HOPE) model (1° with 0.3° equatorial refinement and 29 levels), and 3D Optimal Interpolation (OI) scheme to assimilate temperature, salinity, altimeter derived sea-level anomalies and global sea level trends ((Balmaseda et al., 2008). A selection of historical and real-time ocean analysis products can be seen at http://www.ecmwf.int/products/forecasts/d/charts/ocean.

Mercator-Ocean, France

The Mercator-Ocean reanalysis, referred to as PSY2G2, covers the 1979-present time period and is used at Météo-France for coupled seasonal forecasts. The PSY2G2 is based on the OPA8.2 ocean model in the ORCA2 global configuration at 2° with 0.5° equatorial refinement and 31 levels. In situ temperature and salinity profiles, SST maps and along track SLA data are assimilated weekly using a fixed basis reduced order Kalman filter with the SEEK formulation (Drévillon et al., 2008).

Japan Meteorology Agency (JMA)

The JMA reanalysis, referred to as MOVE/MRI.COM-G (Usui et al. 2006), was implemented in March 2008. The analysis system covers the quasi-global ocean (75°S-75°N) with 1° grids with 0.3° equatorial refinement and 50 levels. It provides pentad and monthly fields from 1979 to present (http://ds.data.jma.go.jp/tcc/tcc/products/clisys/index.html).

Bureau of Meteorology (BOM), Australia

The BOM reanalysis, called PEODAS (POAMA Ensemble Ocean Data Assimilation System, http://poama.bom.gov.au/research/assim/index.htm, has been developed for the period from 1980 to present. It is an approximate form of ensemble Kalman filter system (Yin et al. 2010). Both in situ temperature and salinity observations are assimilated, and current corrections are generated based on the ensemble covariances.

Met Office, United Kingdom

The UK Met Office delivers an objective monthly temperature analysis based on in situ observations with 1° grid and 42 levels (EN3_v2a, Ingleby and Huddleston, 2007). A historical reanalysis for the period 1950 to present is available, and the real time updates have approximately one month lag (http://www.metoffice.gov.uk/hadobs/en3).

National Oceanographic Data Center (NODC), NOAA/USA

The NODC delivers an objective seasonal temperature analysis based on in situ observations. The analysis is at 1° grid and 16 levels ranging from the ocean surface to 700 m in depth from 1955 to 2009 (Levitus et al., 2009).

Comparison of upper ocean heat content

Upper ocean heat content is defined as the average temperature in the upper 300m (hereafter, HC300). HC300 anomalies (HC300a) are derived by removing the 1985-2009 climatology in each data set. Since the EN3 is based on in situ data only with monthly resolution, it is used to as the baseline to compare the other ORAs. The temporal correlation with EN3 is generally high (> 0.8) in the tropical Pacific, North Pacific and North Atlantic (Figure 1). The correlation is poor near the western boundary currents, the Gulf Stream and Kuroshio Extension, which is probably because there are insufficient data to constrain

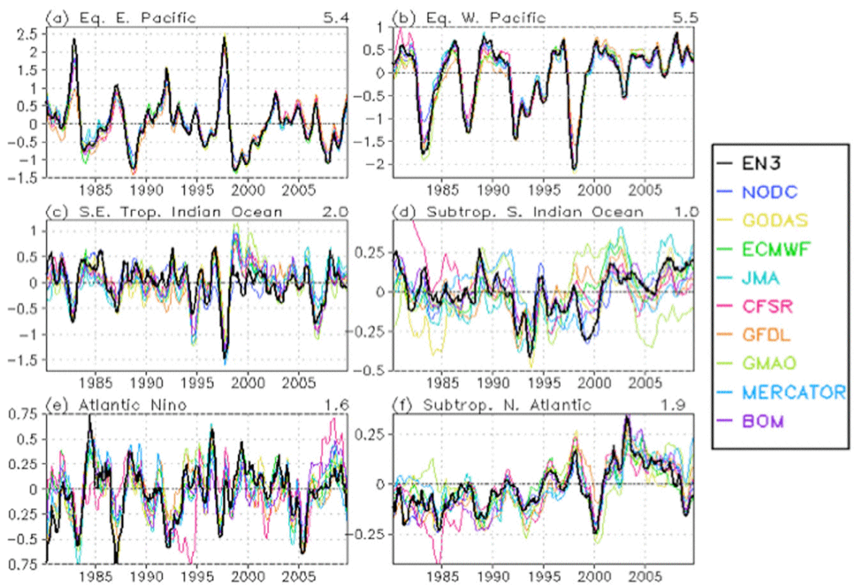

Figure 2. Time series of 7-month running means of HC300a (°C) averaged in (a) the equatorial eastern Pacific (150W-90W, 5S-5N), (b) equatorial western Pacific (130E-170W, 5S-5N), (c) southeast tropical Indian Ocean (90E-110E, 10S-0), (d) subtropical South Indian Ocean (45E-110E, 30S-15S), (e) Atlantic Niño defined as HC300a differences between the region of (20W-20E,1S-0) and (60W-20W,0-10N), and (f) subtropical North Atlantic (80W-10W, 15N-30N). The signal to noise ratio is shown on the right top of each figure.

EN3 in those areas. It is interesting that the correlation is moderately high in the tropical Indian Ocean, and has a pattern resembling the IOD pattern. The correlation is relatively low in the tropical Atlantic, and mid- to high-latitude southern oceans where observations are sparse.

Since analyzed HC300a provides information important for seasonal forecast skill of ENSO, IOD, and tropical Atlantic Niño, a set of HC300a indices characterizing those tropical SST variabilities are intercompared (Fig. 2). The signal to noise ratio (SNR), calculated as the ratio of standard deviation of the ensemble mean and ensemble spread, of HC300a indices is high (~5.4) in the equatorial eastern and western Pacific. The variability of HC300a has a decadal shift: variability is much weaker and the equatorial western Pacific is much warmer after 2000 than before 2000 (Figure 2a-b). We also note that the warming during the 1982/83 (1997/98) El Niño is significantly underestimated by the GFDL (NODC) (Figure 2a). Large negative HC300 anomalies in the southeast tropical Indian Ocean associated with the IOD events in 1982, 1994, 1997 and 2006 were well captured by model-based analyses. (Figure 2c). However, the NODC and EN3, without the benefit of surface forcing to compensate for sparse observations, missed the positive anomaly in 1999 (Figure 2c). The SNRs in the subtropical South Indian Ocean, subtropical North Atlantic and Atlantic Niño are much lower than that for ENSO and IOD (Figure 2d-f). Note that the HC300a in the subtropical South Indian Ocean and subtropical North Atlantic have an upward trend from 1993 to 2009, which is shown in the linear trend map in Figure 3.

The multi-model ensemble trend of HC300 is calculated for 1993-2009 (Fig. 3a) and can be compared with the trend in altimetric sea surface height (Xue et al., 2010b). There are large regions of the ocean where the SNR is low, indicating a large uncertainty in the trend. These are generally areas where the correlation with EN3 is low across many of the ORAs. The SNR is also low in the eastern Equatorial Pacific where the ensemble mean trend is also very low. All ORAs show an increasing (decreasing) HC300 in the western tropical Pacific (subtropical eastern Pacific). The increasing HC300 in the central North Pacific, and a decrease south of Alaska and off the west coast of North America simulated by all ORAs, is consistent with an overall downward trend in the PDO index. The increasing HC300 in the subpolar North Atlantic consistent in all ORAs is related to the weakening of the subpolar gyre since 1995. The increasing trends in the subtropical South Indian Ocean and subtropical North Atlantic are weak, but are consistently simulated by all ORAs.

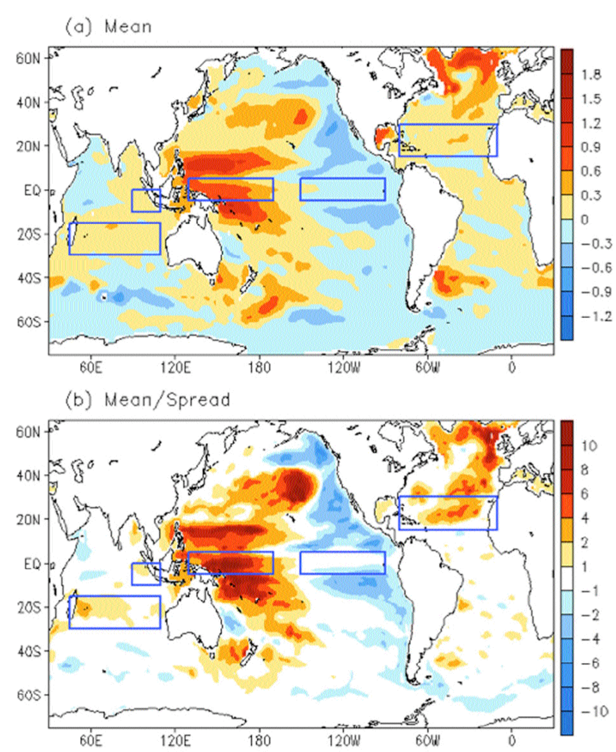

Figure 3. Linear trends of HC300a based on 10 ORAs in 1993–2009 (°C/decade). (a) Ensemble mean, (b) ratio between ensemble mean and ensemble spread. The boxes show the regions used for the time series of the average HC300a in Figure 2.

Summary

Our analysis demonstrates that the current generation of ORAs is promising in providing reliable estimation of global HC300 variability to the extent that they can be used in understanding and monitoring climate signals in HC300. This activity could be extended to routine exchange of ORAs, and implementation of real-time multi-model ensemble HC300 indices in the near future.

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U.S. CLIVAR Director, David Legler, Moves on...

Following a decade of successful leadership at the helm of the U.S. CLIVAR Office, Dr. David Legler assumed his new position as Director of NOAA's Office of Climate Observations within the NOAA Climate Program Office in January 2011. We wish to acknowledge here some of the many contributions by David to stimulate planning and to promote implementation of U.S. CLIVAR science. Beginning in 2001, David established new mechanisms to facilitate communication with the national and international research community including the U.S. CLIVAR website and the *VARIATIONS* newsletter providing updates on evolving program planning, exciting research findings, new funding opportunities, and a calendar of events. Over the years, he worked closely with the Scientific Steering Committee, Panels and Working Groups to identify and scope new research thrusts and with the Interagency Group of NASA, NOAA and NSF managers (and more recently engaging DOE and ONR) to coordinate interagency sponsorship of:

- Field Campaigns to collect high-resolution observational datasets to improve process understanding and address model biases, including EPIC, SALLJEX, NAME, AMMA, DIMES, VOCALS and the upcoming DYNAMO;
- Climate Process Teams to link observational and process-oriented research to modeling for the purpose of addressing key uncertainties in climate models;
- Climate Model Evaluation Projects to increase diagnostic research into the quality of model simulations, leading to more robust evaluations of model predictions and better quantification of uncertainty in projections of future climate;
- Drought in Coupled Models Projects to expand diagnostic research into the physical mechanisms of drought and to evaluate its simulation by climate models;
- Limited lifetime working groups focused on salinity, the Madden Julian Oscillation, western boundary currents, high latitude surface fluxes, drought, decadal predictability, and most recently two new groups on hurricanes and Greenland ice sheet/ocean interactions; and
- Workshops and scientific meetings to foster community engagement on specific research topics, including ocean observing system requirements and integrated Earth system analyses.

Much of U.S. CLIVAR progress can be traced directly to David's skill in soliciting community input to guide climate research directions and fostering commitments by participating funding agencies to ensure their implementation. He departs leaving a strong legacy. The U.S. CLIVAR Scientific Steering Committee, Interagency Group, and Project Office look forward to working with David in his new role and wish him continued success.

U.S. CLIVAR launches two new Working Groups

Hurricane Working Group

A primary focus of climate modeling studies of tropical cyclones has been reproducing the observed climatological pattern of tropical cyclone formation along with its interannual variability. Considerable uncertainties about the mechanisms of tropical cyclone formation and its representation in models remain. While many of the processes that govern observed tropical cyclone formation appear to be small-scale and stochastic in nature, coarser resolution climate models have shown ability to simulate both the climatology and the interannual variation of tropical cyclone numbers. Yet we understand little about the reasons for the sensitivity of tropical cyclone formation to imposed changes in boundary conditions such as sea surface temperature anomalies of the kind caused by interannual variability or by the enhanced greenhouse effect.

Co-chaired by Suzana Camargo (LDEO, Columbia U.), Gabriel Vecchi (NOAA/GFDL), and Kevin Walsh (University of Melbourne, Australia), the Hurricane Working Group (WG) will address these uncertainties by (a) pursuing an improved understanding of interannual variability, and trends, in tropical cyclone activity from the beginning of the 20th century to the present, and (b) quantifying changes in the characteristics of tropical cyclones under a warming climate.

The WG will assess exiting model experiments, coordinate new experiments with a common set of forcings, and provide the output for use by the research, prediction and applications communities. The preliminary list of experiments to be run with high-resolution global climate models includes:

Interannual: Experiments covering 1982-2009 and using Hadley and Reynolds SST products to explore the ability of models to reproduce observed seasonal TC metrics and the sensitivity of model response to uncertainties in SST analysis during the satellite era, and to provide a "potential predictability" baseline.

Climatology: Repeating SST climatology (1982-2005 from Hadley SST) for 10 to 20 years to evaluate the purely stochastic elements of TC metrics and to provide a baseline for idealized perturbation studies.

Global 2K: Repeating SST climatology (as in Climatology experiment) plus a 2K globally-uniform SST anomaly, 10 to 20 years to explore the sensitivity of seasonal TC metrics to uniform SST changes.

Global Warming: CMIP3 SST anomaly climate change experiment with no corresponding increase in CO2 compared with one where AMIP SSTs are used but including the climate change CO2 forcing, to determine the relative importance of the two and help resolve whether AMIP-style runs actually give the correct forcing or not.

Noting that the work proposed would be useful in interpreting CMIP5 results, a near-term aim is to complete publication(s) for inclusion in the upcoming IPCC 5th Assessment Report. A small WG meeting is being planned for January 2012 in connection with AMS Winter Meeting in New Orleans. A larger community workshop will follow near the completion of the WG in 2013.

Greenland Ice Sheet/Ocean Interaction Working Group

Net mass loss from the Greenland Ice Sheet has increased rapidly over the last decade, primarily as a result of the acceleration and retreat of outlet glaciers in western and southeast Greenland. The acceleration is attributed to significant changes in the boundary conditions at the glaciers' termini, which are typically grounded ~600m below sea-level in Greenland's deep fjords. The leading hypothesis is that these changes are due to an increase in ocean-driven submarine melting corresponding to warming of the ocean waters that come in contact with the glaciers.

At present, ice sheet/ocean interactions are not included in climate and ice sheet models and there is strong societal pressure on the scientific community to address this issue and improve sea level change projections. As scientists seek to advance our knowledge of the coupled system, scientific progress is being hindered by the inherent separation of the communities involved. Furthermore, much of the present focus on ice sheet/ocean interactions is on Antarctica where this mechanism has been recognized as relevant for some time. Results derived for Antarctica, however are not immediately applicable to Greenland given the different land/ocean distribution, coastal configuration and large-scale ocean and atmosphere circulations.

The Greenland Ice Sheet/Ocean Interations WG, chaired by Fiamma Straneo (WHOI), Olga Sergienko (Princeton/GFDL) and Patrick Heimbach (MIT), seeks to foster and promote interaction among the diverse oceanographic, glaciological, atmospheric and climate communities, including modelers and field and data scientists within each community, interested in glacier/ocean interactions around Greenland, to advance understanding of processes and ultimately improve their representation in climate models.

The WG will soon begin drafting a paper for submission to EOS or BAMS summarizing the state of knowledge and research on Greenland Ice Sheet/ocean interactions, presenting various disciplinary perspectives, and enumerating key science questions and proposed options on how the community may proceed. A WG meeting to review the manuscript will coincide with the International Glaciological Society meeting on ice/ocean interactions at Scripps in early June 2011. A limited participation workshop, being considered for Winter/Spring 2012, would target communities such as US and Northern European field observation oceanographers; fjord dynamicists, sea ice and atmosphere experts, glaciologist studying outlet glaciers and hydrologists.

Further information on both Working Groups can be found at:http://www.usclivar.org/hurricanewg.php and http://www.usclivar.org/icesheet.php.

U.S. CLIVAR

Calendar of CLIVAR and CLIVAR-related meetings

Further details are available on the U.S. CLIVAR and International CLIVAR web sites: www.usclivar.org and www.clivar.org

VOCALS Science Meeting
21-23 March 2011
Miami, Florida
Attendance: Open
http://www.ed.ucar.edu/projects/vocals

Workshop on Coupled Atmosphere-Ocean-Land Processes in the Tropical Atlantic
23-25 March 2011
Miami, FL
Attendance: Open
http://www.clivar.org/organization/atlantic/meetings/tropical_bias/miami.php

CLIVAR Atlantic Panel Meeting
25-26 March 2011
Miami, FL
Attendance: Invited
http://www.clivar.org/organization/atlantic/meetings/aip-11/aip11.php

CLIVAR VAMOS Panel Meeting
25-26 March 2011
Miami, FL
Attendance: Invited
http://www.clivar.org/organization/vamos/Meetings/VPM14_meet.php

Deep Ocean Workshop/Ocean Observations Panel for Climate-15 Meeting
30 March -2 April 2011
Paris, France
Attendance: Invited
http://ioc-goos-oopc.org/index.php

WCRP Joint Scientific Committee
4-8 April 2011
Exeter, UK
Attendance: Invited
http://www.clivar.org/calendar/calendar_all.php

34th International Symposium on Remote Sensing of the Environmnet
10-15 April 2011
Sydney, Australia
Attendance: Open
http://isrse34.org/

11th Conference on Polar Meteorology and Oceanography
2-4 May 2011
Boston, MA
Attendance: Open
http://www.ametsoc.org/MEET/fainst/2011polar.html

CLIVAR SSG-18 Meeting
2-5 May 2011
Paris, France
Attendance: Invited
http://www.clivar.org/calendar/

Workshop on Advances in the Use of Historical Marine Climate Data (MARCDAT)
2-6 May 2011
Frascati, Italy
Attendance: Limited
http://icoads.noaa.gov/marcdat3/

NCAR Advanced Study Colloquium: Statistical Assessment of Extreme Weather Phenomena under Climate Change
6-24 June 2011
Boulder, CO
Attendance: Limited
http://www.asp.ucar.edu/colloquium/2011/index.php

First XBT Workshop
7-8 July 2011
Melbourne, Australia
Attendance: Open
http://www.aoml.noaa.gov/phod/goos/meetings/2011/XSW/

Past, Present and Future Change in the Atlantic Meridional Overturning Circulation
12-15 July 2011
Bristol, UK
Attendance: Open
http://www.noc.soton.ac.uk/rapid/ic2011

U.S. CLIVAR Summit
19-21 July 2011
Woods Hole, MA
Attendance: Invited
http://www.usclivar.org

WCRP Open Science Conference
24-28 October 2011
Denver, CO
Attendance: Open
http://www.wcrp-climate.org/conference2011/

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