WCRP-JCOMM Workshop on Coordinated Global Wave Climate Projections (COWCLIP)

WMO Headquarters, Geneva, Switzerland, 11 – 13 April 2011

By Mark Hemer, Xiaolan Wang, Ralf Weisse and the COWCLIP Team

WMO/TD-No. 1581

JCOMM Technical Report No. 55

WCRP Informal Report No. 22/2011

2011

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NOTE

C O N T E N T S

1. Introduction

The Coordinated Ocean Wave Climate Projections (COWCLIP) workshop was held on April 11-13, 2011, at the World Meteorological Organization (WMO) in Geneva, Switzerland, with the support of the World Climate Research Programme and the Joint Technical Commission for Oceanography and Marine Meteorology of WMO and Intergovernmental Oceanographic Commission (IOC) of UNESCO. The workshop aimed to bring together international researchers with interest in wind wave climate variability and change, to discuss the potential path forward for a collaborative working group to address challenges in this field following the publication of proposed activities in 2010 (Hemer *et al*., 2010). This document summarises the research questions discussed at the workshop, in order to present a community view of the key scientific questions, challenges and recommendations relevant to wind-waves in a changing climate.

COWCLIP aims to generate wave climate projections (ultimately of global extent) and aid comprehensive assessments of their cascading uncertainty by:

- Providing a systematic, community-based framework and infrastructure to support validation, intercomparison, documentation and data access for wave climate projections forced from CMIP5 datasets,
- To describe best practice for regional wave climate projections, and
- Engaging the interests of the wind-wave community into the wider climate community and ultimately developing coupled wind-wave Atmosphere-Ocean global climate models in order to derive quantitative estimates of wind-wave driven feedbacks in the coupled climate system.

Approximately 30 researchers attended the workshop from 18 countries (see Appendix A). The workshop consisted of 22 presentations, including an invited presentation given by Dr Baylor Fox-Kemper of CIRES, University of Colorado, Boulder, on behalf of the WGCM and CMIP communities, to introduce WGCM and CMIP, and explore potential benefits and opportunities for the waves community within these programs. The other 21 presentations were distributed over four themes as follows:

- Global wave climate projections
- Regional wave climate projections
- Coupled wind-wave-climate modelling
- Historical wave climate variability and change

The workshop schedule and a compilation of the presentation abstracts are appended to this document as Appendices B and C respectively. Four targeted discussion sessions were held over the three days each focussing on one of the above themes. On the final day of the workshop, these discussions were focussed to ascertain community derived recommendations for each of these themes. In each theme, the discussion aimed to identify the key science questions, technical aspects, and a list of recommendations with an indication of an associated timeline. A summary of the outcomes of these discussions for each of these themes can be found below.

Publication of papers relevant to the COWCLIP themes in a special issue of a journal was discussed. Too few groups were able to commit to a contribution and consequently no further action will be taken towards this at this time, however the COWCLIP group will begin assembling a bibliography of relevant literature so that contributions can be assessed at the next meeting.

2. Global wave climate projections

Key science questions

A number of science questions relating to global projections were identified. In no particular order, these include:

<u>*Data-forcing of wave climate:*</u>

- Historical wind-wave records provide an integrated indicator of marine winds. Using waves as a diagnostic, what skill do climate models have at representing present climate? Can climate models be used for marine-meteorological applications? How do CMIP5 marine winds compare to those from CMIP3?
- How well do climate model derived wave climate fields compare with the climatological record (consideration of means and extremes)?
- Are marine winds derived from higher resolution climate models (e.g., CMIP5 time-slice experiments) any better than coarse resolution winds?

Models and Methodologies to characterize wave climate:

- How do different methods of deriving wave climate projections (e.g., statistical vs dynamical; bias-adjustment influence) inter-compare? One hypothesis raised was that this source of uncertainty was small in comparison to other sources of uncertainty, and shared community effort should concentrate on determining the range of wave climate projections based on a larger ensemble of climate model integrations, regardless of approach taken. The counterargument was that quantifying this source of uncertainty is central to this community.
- What is the minimum spatial resolution of wave model required to obtain adequate wind-wave climatologies for climate research?
- Is there potential for improvement in global wave model representation of wave climate (improved atmospheric forcing – e.g., cyclones), wave parameterisations?
- Would a statistical relationship calibrated for the present climate remain valid for a future climate? There is a need to test time-transferability of statistical models calibrated for making projections.
- What is the magnitude of uncertainty surrounding projected changes in wave climate, and how do we best sample the cascading levels of uncertainty associated with emission scenarios, climate model uncertainty, and downscaling steps.

Wave climate projections outputs/results:

- To what extent can present wave models simulate the present global wave climate (which features are reproduced, which not)?
- What are the expected changes in global wave climate, including assessment of means and extremes?
- Are there robust features in projected wave climate changes (detection and attribution)?
- When do projected changes emerge from background variability? Consideration of interannual/decadal variability in the wind-wave climate.

Technical aspects

Several methods of deriving wave climate projections are being used within the community. These include dynamical and statistical methods. In the dynamical approach, surface forcing is being derived from climate models (global or regionally downscaled) and used to force a spectral wave model. Some researchers presented bias-adjustment (both of output wave properties and of forcing winds were presented) to improve representation of the current wave climate, and assumed a time invariant bias adjustment to derive future projections. This approach can downscale to regional applications by archiving spectral time-series which may be used as boundary conditions. The statistical approach uses current climate reanalyses (atmospheric and wave) to establish a statistical relationship between the predictor (e.g., MSLP, 10-m winds) and the predictand (e.g., most commonly Hs, but joint probability of Hs and Tp, energy flux vector, and wave spectrum were also presented). The statistical relationship established is then applied to projections of the predictor taken from the climate models to derive projections of the predictand. These relationships could be built up from global or regional scale studies. Another approach which was not covered by any presentations was the identification of useful diagnostics of wave climate and wave-wind feedbacks on the climate system, but was raised in discussion as requiring future research effort.

A clear technical need for global wave projections was identified as providing open boundary swell wave conditions for regional coastal impacts of climate change studies. Ultimately spectral data archived at grid cells adjacent to coastal regions is required to support these activities. The achievability of this is uncertain given the volume of data which must be archived, given global coast scale, long time periods, and multiple climate scenarios.

To support intercomparison between multiple datasets, various project details require standardisation within the collaborative community. Datasets which received mention as suitable sources representing the present wave climate (for comparison) included the ECMWF waves reanalyses (ERA-40, the updated ERA-Interim, and its planned successor, ERA-clim), the Altimeter Hs record, the VOS dataset, and the NOAA Climate Forecast System Reanalysis (NCFSR) forced WaveWatchIII hindcast currently underway. The period 1979-2009, common to both the extended ERA-Interim and NCFSR hindcast, was noted as a suitable representative 30-yr present climate control period for ongoing wave studies. For future time-slices, the availability of high temporal (and spatial) resolution surface wind outputs from the CMIP5 experiments for the periods 2026-2045 (or 2026-2035 for decadal and time-slice experiments), and 2080-2100 (for the long-term experiments) dictate these periods as the most suitable to concentrate development of a community ensemble of wave climate projections. The community has concerns about the short 2010-yr period over which high temporal resolution outputs will be available from the CMIP5 mid-century (2026-2035) time-slice experiments. A single decade is considered too short to derive robust statistics of change, and it is anticipated that any potential trends signal in this near-term future run will not be distinguishable from the background variability. Twenty year time-slices were considered more suitable (2026-2045 and 2080-2100), but the community recommends high temporal resolution data be available over 30-yr time-slices to address these issues.

Recommendations

A key recommended objective of COWCLIP is the coordination of global wave projections for intercomparison between international research groups, to understand uncertainty within the community ensemble of wave climate projections. The proposed timeline, in order to maximise impact, is for inclusion in IPCC AR5 (submitted before end July 2012). There are key challenges in that development of wave climate projections, particularly dynamical projections, is computationally expensive, time consuming, and are dependent on high temporal (and spatial) resolution surface wind data from the Coupled Model Intercomparison Project (CMIP5) global climate models (which is being archived for only select model runs).

With CMIP5 data only becoming available at the time of the workshop (April 2011), and the tight AR5 timeline, the proposed activities must be concentrated (a pilot project phase on the AR5 timeline), and a larger COWCLIP production phase be targeted at any future IPCC Assessments. The key objectives of the pilot phase of the project, addressed within a community paper summarising the outcomes, will be to raise the profile of wave climate issues within the climate community, to produce recommendations as to what is needed to support COWCLIP activities from CMIP, and what is expected from the coastal impacts community, and compile comprehensive details on CPU and disk space for processing and archive requirements. It was recommended that research groups currently developing wave climate projections (from CMIP3 or CMIP5 experiments – approximately 5 groups) aim to submit individual papers within the next 12 months. The 2011 Hawaii waves workshop (proposed wave climate session) will provide a timely opportunity to reassess progress on these activities. Following this, a 2^{nd} COWCLIP workshop is recommended to be held in early 2012, to intercompare results of these studies with the aim of submitting a community consensus paper before July 2012 for inclusion in the AR5. It is intended that demonstration of COWCLIP within the pilot phase of the project will lead to greater community involvement in ongoing activities.

On a longer time frame (with a view to IPCC AR6), COWCLIP aims to have wave models run routinely with the CMIP climate models, to develop wave climate projections as an added climate parameter to assess future climate change. This ‘production phase’ of COWCLIP will follow a designed approach, aiming to sample evenly over the full sample space (scenarios, CMIP models), to produce a community ensemble of global wave climate projections (using dynamical and statistical projection approaches, with the aim of exploiting advantages of each technique). Two key experiments are noted, aiming to quantify uncertainty: a) within the wave projection approaches for a common CMIP run set; and b) between the projected wave climate for ensembles of CMIP run sets. To support these activities, a common set of analyses, procedures and data policies will be established.

3. Regional wave climate projections

A high number of regional studies were presented at the workshop. These studies are typically carried out to address notable regional concerns of funding bodies, and other regions with potentially greater risk (e.g., higher coastal population, larger potential changes) are often overlooked. These studies are also limited in that they sample across only a limited set of climate models and scenarios. Consequently, the range of uncertainty within these studies can not be reliably quantified.

Key science questions

All of the science questions identified for global wave climate projections are equally valid for regional studies. Other questions identified specific to regional studies include:
- Is there added value in high resolution atmospheric and/or wind-wave downscaling in assessing the (wave) climate signal for regional seas?
- How best is the combined influence of sea-level rise and projected changes in storm surge and wave climate characterised?
- What is the added value of coupling a regional climate model with wave and ocean models?

Technical aspects

As with the science questions, all of the technical aspects identified concerning global wave projection studies are equally valid for regional studies. It was noted that the regional studies provide valuable forcing boundary conditions for downstream coastal and regional evolution/morphological models, in addition to input to regional coastal impact and coastal adaptation assessments. A list of parameters used to support these activities includes: Hs distribution, Wave energy flux vectors, persistence of storms, Wave Directions, Wave Periods, and joint probability distributions of these variables.

Recommendations

It was recognised that given individual research groups independent regional interests, it would be difficult to establish a community ensemble for any particular region. However, this is currently possible in particular regions where overlap between existing studies occurs (e.g., North Sea). In these locations, it was recommended that the groups involved with those studies carry out an intercomparison of results. It was recommended that some regions should be focussed on as demonstration regions, whether that be for reasons that there are existing studies (as above), or that the potential impacts for the region are likely to be larger (e.g., the Arctic for reasons relating to changing sea-ice coverage, Spain, South America or the low-lying countries).

A possible task for this community is to combine available regional simulations and projections for the many regions of the global ocean for which studies have been undertaken, in order to derive a global perspective of projected wave climate change from these studies. Such a global picture may then be compared with global projections determined by other researchers.

It was noted that regional studies are strongly dependent on the needs of the impacts community, who should be canvassed to determine how best COWCLIP could serve their needs. On an AR5 timescale, it was recommended that individual studies submit work for publishing prior to July 2012, to develop a limited regional picture of projected wave climate change.

4. Coupled wind-wave climate modelling

Key science questions

A number of sea-state dependent processes are currently parameterised in the climate models using wind-dependent parameterisations. These include the momentum fluxes (e.g., influence of sea-state dependent drag on the air-sea momentum transfer), heat fluxes (e.g., wave driven turbulence and approximate Langmuir circulations driving mixing in the surface ocean mixed layer, and also wave dependent variability of the sensible and latent heat fluxes into the atmosphere), mass fluxes (e.g., marine aerosol production into the atmosphere, and bubble injection by breaking waves into the ocean), the radiation budget (e.g., the increased albedo of whitecapping waves), and the influence of waves on the extent of the marginal ice zone (affecting all of the above processes). Presently, only the air-sea momentum flux and the surface ocean mixing are receiving attention in a climate modelling sense. While the short-term aims of COWCLIP are to determine wave climate projections in an off-line (one-way coupled) sense, the long-term goal is for waves to become a standard component of the coupled climate system, with waves coupled into the coupled climate models. Such an approach has the advantages of (1) more physically representative parameterisations of key processes at the air-sea interface, and (2) removes the need for these un-coupled wave model runs to generate wave information, needed by both the impacts community but also simply additional parameters to assess the coupled climate system. The key science question related to this component of COWCLIP is how large are the surface wave driven feedbacks, associated with each of the above processes, on the coupled climate system, and can we identify the relative magnitude of each of these processes. Other science questions which arise include:

- Does the inclusion of wave dependent parameterisations in the climate models improve model skill?
- Which climate model biases are improved, and which are worsened?
- How difficult is it to include wave dependent parameterisations into climate models?
- Are present wave dependent parameterisations of sufficient quality and global applicability to be used in climate models, or are adaptations and improvements required?
- If wave models are coupled into a climate model as a component, with the necessary reduction in resolution required by memory and speed constraints, will the wave forecasts be sufficiently accurate to a) drive parameterizations, and b) be used as wave climate forecasts?
- Are the coupled models wind and other fields sufficiently accurate to drive an online wave model?
- Does the inclusion of wave dependent parameterisations in the climate models stabilise or destabilise the coupled climate system
- What are the most useful diagnostics to assess the influence of including wave dependent parameterisations?

Technical aspects

There are considerable technical computational challenges facing the advance of coupling waves into the coupled atmosphere-ocean climate models. One of the key limitations is the computing overhead of adding a wave model into the coupled climate system, and whether this computing cost offers sufficient benefit to bother. This is a key task of the few modelling centres currently working to implement wave models within their coupled climate model systems.

The implementation of wave dependent parameterisations will potentially lead to stability problems in the climate model, and the time-consuming task of re-tuning other climate model parameters is required. However, retuning after CMIP5 is expected at all modelling centres, so the COWCLIP schedule for inclusion in CMIP6/AR6 is timely.

Presently, there is a need for stronger communication between the wave modelling community and the climate modelling community to implement these parameterisations. Few researchers have the knowledge required to bridge the gap between these communities. It would be good to continue welcoming those scientists who are knowledgeable or interested in bridging the gap to future COWCLIP meetings.

Different approaches are being used to implement the wave dependent parameterisations into the climate models. Some (regional) models have implemented the wave model as a subroutine of the climate model, while global climate models are tending to implement the wave model using a coupler.

Recommendations

The most immediate recommendation is for the COWCLIP community to compile a community review paper of the range of wave dependent processes in the coupled climate system, with the aim of presenting preliminary estimates of the relative influence of each process on the coupled system. While this recommendation has no specific deadline, it is anticipated to produce this over the next 12 months.

A select few modelling centres are currently implementing or have already implemented wave models into their coupled climate models. These include CESM, GFDL, ECMWF and ACCESS. On an AR6 timeframe, it is recommended that these centres work together with the aim of addressing the key questions outlined above. If wave dependent parameterisations are proven to have significant influence on the coupled climate system, it is anticipated that other climate modelling centres will follow suit coupling waves with their climate models. Future COWCLIP meetings should continue to facilitate these plans.

5. Historical wind-wave climate variability and change

Key science questions

A key component of wave climate research is understanding historical wave climate variability, and its drivers (on seasonal, interannual, decadal and centennial timescales). With COWCLIP's aims of generating wave climate projections, it is imperative that the natural modes of variability are understood. While this component of COWCLIP activities is the most advanced, several key science questions remain, including:

- What is the relationship between key coastal processes (e.g., shoreline position, coastal sediment budgets, etc) and wave climate?
- How does the power spectrum of wave climate (hourly to centennial time-scales) compare to other climate variables?
- Can we identify suitable proxy records for historical variability of wave climate?
- What is the relationship between wave climate and existing climate indices?
- Can we define a specific climate index for wave climate applications (e.g., NAO or a similarly derived index for North Atlantic, SAM in Southern Ocean)?
- What other datasets are available which can be exploited for wave climate studies (e.g., the COASTALT project)?
- Statistical downscaling approaches typically assume that a statistical relationship calibrated for one climate condition (e.g., the present climate) will hold in a different climate condition (e.g. a future climate). Is such an assumption valid, and to what extent? Observations and reanalysis data can be used to test time-transferability of statistical relationships.
- How well do climate model derived wave climates compare to wave reanalyses for present climate conditions (including trends)?
- Is present interannual and interdecadal variability in the wave climate adequately characterised?

- Can historical wave climate trends be attributed to human-induced climate change, or other factors?
- Wave climate is presently widely described by integrated wave parameters, Hs, Tm or Tp and Dm or Dp. Are other descriptors more suitable?

Technical aspects

The key limitation of understanding the historical variability of wave climate is the length of observational records. The longest in-situ observational wave records are approximately 40 years in length. The satellite altimeter record is approximately 25 years in length. Wave reanalyses vary in length up to 45 years (ERA-40), and potentially ~100 years with ERA-CLIM plans. With these short records, resolving long term trends with respect to natural decadal (or longer) variability is not possible. Coupled climate modelling including waves, as described in the last section, may aid in lengthening the hindcast records or providing long synthetic datasets for comparison.

A further issue in establishing a global picture of historical variability and change is the limited availability of in-situ data from many custodian organisations which do not openly provide their data for the research community.

Recommendations

In the IPCC AR4, discussion on historical variability in wave climate assessed changes in wave height only. A clear recommendation of the COWCLIP community was that in future assessments this focus be broadened to ensure that a more complete representation of wave climate is considered. This should include joint probability distributions of height and period, energy flux and directional characteristics.

No specific timeline was indicated for studies within this theme. It was noted that clear messages on historical wave climate variability are now recognised, and being summarised within current assessments for the IPCC AR5.

6. Summary

The COWCLIP workshop was successful on several fronts:

- The workshop brought together a small group of researchers with closely aligned research objectives. A core working group have agreed to progress COWCLIP activities following the recommendations taken from the workshop.

- The workshop presentations, archived on the JCOMM workshop website, provide a useful documentation of the range of projection methodologies which are currently being applied to wave climate projection studies.

- The COWCLIP community have identified a range of key science questions addressing the four themes which are encompassed within COWCLIP.

- A working protocol has been devised for a pilot phase of COWCLIP activities. This phase is closely aligned with existing research activities, with the aim of producing usable outputs within the IPCC AR5. A preliminary plan for ongoing COWCLIP activities beyond the AR5 timeline has also been considered.

- Several challenges remain on how to advance COWCLIP activities. These include funding restraints, the need to maintain momentum, and the tight timelines to maximise impact with inclusion in the AR5. The 2011 Hawaii waves workshop (wave climate session), and 2nd COWCLIP workshop planned for early 2012, most likely in Europe, will aim to make further advance against these issues.

7. Acknowledgements

The workshop organisers would like to acknowledge the support of the World Climate Research Programme and the WMO/IOC Joint Technical Commission on Oceanography and Marine Meteorology for their logistical support of the Coordinated Ocean Wave Projections workshop. We would also like to acknowledge the considerable support organising this workshop by Val Swail, of Environment Canada, who was instrumental in the success of the workshop but was unable to attend. Further financial support of workshop logistics was provided by the CSIRO Wealth from Oceans National Research Flagship and the Australian Government Australian Climate Change Science Program.

8. References

Hemer et al. (2010) Modelling proposal: Coordinated global ocean wave projections. *Bull. Amer. Met. Soc.*, DOI: 10.1175/2009BAMS2951.1

Annex 1

COWCLIP Workshop Attendees

Attendees

Ole Johan Aarnes	Norwegian Met Institute	Norway	oyvind.breivik@met.no
Fabrice Ardhuin	IFREMER	France	Fabrice.Ardhuin@ifremer.fr
Jean Bidlot	ECMWF	UK	jean.bidlot@ecmwf.int
Oyvind Breivik	Norwegian Met Institute	Norway	oyvind.breivik@met.no
Sofia Caires	Deltares	The Netherlands	sofia.caires@deltares.nl
Jonas Takeo Carvalho	Brazilian Navy Hydrographic Centre	Brazil	jtcarvalho@gmail.com
Merce Casas I Prat	Universitat Politecnica Catalunya	Spain	merce.casas@upc.edu
Elodie Charles	BRGM	France	e.charles@brgm.fr
Yalin Fan	GFDL	USA	yalin.fan@noaa.gov
Baylor Fox-Kemper	CIRES/CU-Boulder	USA	bfk@colorado.edu
Iris Grabemann	Helmholtz-Zentrum Geestacht	Germany	iris.grabemann@hzg.de
Nikolaus Groll	Helmholtz-Zentrum Geestacht	Germany	nikolaus.groll@hzg.de
Heinz Guenther	Helmholtz-Zentrum Geestacht	Germany	heinz.guenther@hzg.de
Mark Hemer	CAWCR	Australia	mark.hemer@csiro.au
Kiryong Kang	Korean Met Agency	Korea	krkang@kma.go.kr
Amelie Laugel	Saint-Venant Lab	France	amelie.laugel@edf.fr
Piero Lionello	University of Salento	Italy	piero.lionello@pd.infn.it
Giovanni Mattarolo	Saint-Venant Lab	France	amelie.laugel@edf.fr
Fernando J. Mendez	IH Cantabria	Spain	mendezf@unican.es
Melisa Menendez	IH Cantabria	Spain	menendezm@unican.es
Nobuhito Mori	Kyoto University	Japan	mori.nobuhito.8a@kyoto-u.ac.jp
Francisco Ocampo Torres	Oceanografia Fisica	Mexico	ocampo@cicese.mx
Lars Roed	Norwegian Met Institute	Norway	lars.roed@met.no
Nadia Roji	CINAV	Portugal	nadia.sofia.rijo@marinha.pt
Morten Rugbjerg	DHIGroup	Denmark	mnr@dhigroup.com
Vladimir Ryabinin	WCRP	Switzerland	vryabinin@wmo.int
Alvaro Semedo	Escola Naval and Uppsala Universitet	Portugal/Sweden	alvaro.semedo@met.uu.se
Xiaolan Wang	Environment Canada	Canada	xiaolan.wang@ec.gc.ca
Ralf Weisse	Helmholtz-Zentrum Geestacht	Germany	ralf.weisse@hzg.de
Judith Wolf	NOC Liverpool	UK	jaw@pol.ac.uk

Late Apologies

Francois Boucquet	UK MetOffice	UK	francois.bocquet@metoffice.gov.uk
Jens Debernard	Norwegian Met Institute	Norway	jens.debernard@met.no
Greg Flato	Environment Canada	Canada	greg.flato@ec.gc.ca
Sergey Gulev	IORAS	Russia	Sergey Gulev [gul@sail.msk.ru]
William Perrie	Bedford Institute Oceanography	Canada	william.perrie@dfo-mpo.gc.ca
Val Swail	Environment Canada	Canada	val.swail@ec.gc.ca
Kwok Fai Cheung	Uni. Hawaii Manoa	USA	cheung@hawaii.edu
Tomohiro Yasuda	Kyoto University	Japan	yasuda.tomohiro.4x@kyoto-u.ac.jp

Other Apologies

Alexander Babanin	Swinburne University	Australia	ababanin@groupwise.swinburne.edu.au
Hendrik Tolman	NOAAMetOffice	USA	hendrik.tolman@noaa.gov
Cesar Andrade	University of Lisbon	Portugal	candrade@fc.ul.pt
Carlos Guedes Soares	Technical University of Lisbon	Portugal	guedess@mar.ist.utl.pt

Annex 2

Meeting Schedule

1 **Monday 11th April, 2011**

1.A Opening and Welcome

08h30-09h00 Registration
09h00-09h10 Welcome
09h10-09h20 *JCOMM/*WMO Interactions on Ocean Matters
by Edgard Cabrera, WMO
09h20-09h30 *WCRP introduction*
by Vladimir Ryabinin, WCRP
09h30-10h00 COWCLIP - an introduction
by Hemer, CSIRO
10h00-10h30 **Morning Tea**

1.B Regional Projections 1 : Mediterranean

10h30-10h50 Statistical downscaling of extreme wave climate
by Izaguirre et al, IH Cantabria
10h50-11h10 A hybrid system to downscale wave climate to coastal areas
by Camus et al, IH Cantabria
11h10-11h30 Wave climate projections in the NW Mediterranean
by Casas-Prat and Sierra, UPC
11h30-11h50 Regional wave climate projection studies in the Mediterranean Sea
by Lionello, U.Salento
11h50-12h20 Discussion
12h20-13h20 **Lunch**

1.C Regional Projections 1 : North Sea Projections

13h20-13h40 North Sea wave climate projections for anthropogenic future climate change: an ensemble study
by Grabemann et al, HZG
13h40-14h00 Regional wave climate simulations at the Helmholtz-Zentrum Geestacht, Institute for Coastal Research
by Weisse et al, HZG
14h00-14h20 Discussion

1.D Past Climate

14h20-14h40 Present and future global wave data sets from ECMWF re-analyses and their relevance for climate studies
by Bidlot, ECMWF
14h40-15h00 Wave climate and direct computation of wave extremes estimated from 10 years of EPS prognoses
by Breivik, NMI
15h00-15h30 **Afternoon Tea**

1. **Monday 11th April, 2011 (Continued)**

1.D Past Climate (Continued)

15h30-15h50 Numerical Study of Wind Wave Climatology over NW Pacific using Operational Forecasting System in KMA
by Kang et al, KMA
15h50-16h10 Analysis of wave climate, observations and models
by Ardhuin et al, IFREMER
16h10-16h40 Discussion
16h40-17h40 Targeted Discussion: Past Climate

2 Tuesday 12th April, 2011

2.A Global wave climate projections

09h00-09h20 Statistical reconstruction and projection of ocean waves
by Wang et al, Environment Canada

09h20-09h40 Dynamic Projection of Future Wave Climate Projection Change in Global Scale
by Mori et al, Kyoto U.

09h40-10h00 Impact of a warmer climate on the global wave field: Preliminary results
by Semedo et al, CINAV and Uppsala University

10h00-10h30 Discussion

10h30-11h00 **Morning Tea**

2.B

Regional Projections 2 : Atlantic Coast

11h00-11h20 The wave climate of the NW European Continental Shelf
by Wolf and Bricheno, NOC

11h20-11h40 Present and future wave climate analysis along the French mainland Atlantic coast, using wave dynamical downscaling
by Charles et al, BRGM

11h40-12h00 Dynamical downscaling of regional wave climate in the Northern North Atlantic: results and challenges
by Debenard and Roed, NMI

12h00-12h20 Exploring uncertainty in dynamical wave projection studies
by Hemer et al, CSIRO

12h20-12h40 On the relevance of time and spatial variability of long term wave hindcast on energy resources evaluation and its potential implications onto wave climate projection uncertainties
by Ocampo-Torres, CICESE

12h40-13h40 **Lunch**

2. Tuesday 12th April (Continued)

2.C Preliminary COWCLIP discussions

13h40-14h30 Invited talk (WGCM and CMIP)
by Baylor Fox Kemper, CIRES/UC-Boulder)

14h30-15h30 Targeted Discussion: COWCLIP future activities

15h30-16h00 **Afternoon Tea**

2.D Coupling

16h00-16h20 Simulated wave climatology during the past 30 years and wave climate projection in the late 21st Century
by Fan et al, NOAA/GFDL

16h20-16h40 Two-way coupling between surface gravity waves and climate
by Fox-Kemper et al, CIRES/UC-Boulder

16h40-17h00 Discussion

17h00-18h00 Targeted Discussion: coupling

3 Wednesday 13th April, 2011

3.A COWCLIP Summary Discussions.

09h00-10h30 Key Science Questions and Recommendation/Actions

10h30-11h00 **Morning Tea**

11h00-13h00 Continuation of Summary Discussions.

13h00 Meeting closed.

Annex 3

Meeting Abstracts (Author alphabetical order)

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Analysis of wave climate, observations and models

Fabrice Ardhuin, Abel Balanche, Pierre Queffeulou and Eleonore Stutzmann
IFREMER, France

We examine the correlations and trends between seismic noise, satellite altimeter data and numerical wave models, over the past 20 to 30 years for the North Pacific and North Atlantic. The examination of seismic noise at the Berkeley seismic station (BKS) shows that it is highly correlatied and waves offshore central California and, after identifying particular events, can be used to reconstruct wave time series with high accuracy (r= 0.93 for daily mean Hs). Other seismic stations, in particular in western Europe are instead sensitive to waves over a very large area that covers a good part of the North Atlantic. This is investigated using the Finnish station of Kevo (KEV) and the Scottish station of Eskadelamuir (ESK). Based on modeled wave spectra using the WAVEWATCH **III** model, we estimate the mean spatial distribution of wave-related seismic sources for these two stations and verify that the daily mean noise level is well correlated with the area-averaged wave heights, as inferred from satellite altimeter data (r=0.86). These empirical relationships are then used to verified the trends in wave heights from various sub-regions of the North Atlantic. The seismic data is finally used to correct the time-dependent bias in the numerical wave model hindcasts based on the second NCEP-NCAR reanalysis.

Present and future global wave data sets from ECMWF re-analyses and their relevance for climate studies.

Jean-Raymond Bidlot
European Centre for Medium-range Weather Forecasts
Reading, UK

Unlike the conventional records, reanalysis produces a complete global view of the climate, encompassing many essential climate variables in a physically consistent framework. This includes an active wave model component for the proper description of the momentum flux at the surface of the oceans. Global wave model data are thus produced and archived.

The current reanalysis project from ECMWF – ERA-Interim – has now reached a major milestone after completing over 22 years of reanalysis from 1989 to end of 2010. It is now being extended forward in time to cover the period since 1979. This latest reanalysis follows from the experience of the previous reanalysis - ERA40. The wave data in ERA-Interim have benefitted considerably from improvements of the system with respect to ERA40.

When completed, ERA-Interim will cover a period from 1979 to present time, allowing climate studies of the recent decades. The next big reanalysis effort – ERA-CLIM – has just started. ERA-CLIM will develop observational datasets suitable for global climate studies, with a focus on the past 100 years. These datasets will include atmospheric, oceanic, and terrestrial observations from a variety of sources, high-resolution global reanalysis products derived from the observations, and associated data quality information needed for climate applications. The project will use existing climate data records and make a substantial contribution to filling known gaps in these records. Proposed data recovery efforts will focus on upper-air observations made in the first half of the 20th century, as well as near-surface observations of wind and humidity, in all regions of the globe.

Climate driven change in waves in the North Atlantic and around the UK

François-Xavier Bocquet and Tom Howard
Met Office, Fitzroy Road, Exeter, EX1 3PB, UK

The many offshore marine structures and coastal defences sited around UK seas are designed with expected lifetimes of 10s to 100s of years and to withstand extreme events with long return periods. Despite recent advances in climate prediction, a majority of designs remain based on observed or reanalysis metocean datasets due to their known performance in capturing extreme cases.

The capability to run high-resolution Regional Climate Models (RCMs) raises the possibility that atmospheric forcing fields can be generated which have the necessary detail and intensity to force representative high energy responses in the ocean system (surge and waves). A new project a the Met Office aims to test this capability by making direct comparisons of RCM forced wave model data with existing state of the art hindcast data.

This project will use winds from an 11 member perturbed physics ensemble of global HadCM3 runs, under the A1B emissions scenario, and from a corresponding 12km RCM ensemble centered on the UK to force a set of wave climate runs. These will then be used to create an estimate of the future wave climate, using the WAVEWATCH III model, and the uncertainty associated with it.

The first stage of the work is the validation of the wave model data obtained for the global domain runs by benchmarking it against data from ERA40/ERAI forced WW3 runs, which provide a suitable wave climatology. Preliminary validation statistics are presented here for the global model comparing the uncertainty plume from the PPE runs with the actual climate for the reanalysis period.

The second stage will analyse the future climate projections for both the global and regional climate models.

Wave climate and direct computation of wave extremes estimated from 10 years of EPS prognoses

Oyvind Breivik.
Norwegian Meteorological Institute.

The ECMWF ensemble prediction system (EPS) has been running for more than 10 years, providing a unique source of wave climate information. A comparison with wave buoys in the North Sea and the North Atlantic reveals that the wave climate at +240 hours forecast time is as good or even better than at analysis time. The correlation is however very low, both between members and between model and observations. This allows us to handle the individual ensemble members as random draws from a climatology. The model ensemble is large enough (two model integrations per day and 51 ensemble members) to allow direct computation of wave height extremes as very small exceedance levels (or equivalently return values) can be estimated without resorting to the extrapolation methods traditionally required in extreme value analysis. We will present some preliminary results from the analysis of the EPS and assess their usefulness both for establishing the average wave climate and direct computation of wave height extremes.

A hybrid system to downscale wave climate to coastal areas

Paula Camus, Cristina Izaguirre, Inigo J. Losada, Fernando J. Mendez, Raul Medina

Environmental Hydraulics Institute "IH Cantabria", Universidad de Cantabria, Spain

Wave climate projections using wave generation numerical models are adequate to improve the knowledge of large-scale (say 0.1 to 1º spatial resolution) future wave climates. However, coastal wave climate requires a more detailed spatial resolution (say, 100 m) in order to correctly evaluate different coastal processes. This specific problem of downscaling, enhancing the spatial resolution and defining in detail shallow water areas, is called "wave propagation" and usually requires numerical models that consider the wave propagation processes such as refraction, shoaling, diffraction and dissipation by wave breaking.

In this work, a hybrid methodology to determine high-resolution wave climate in coastal areas, based on statistical and dynamical downscaling, is proposed. The statistical downscaling includes the use of classification (self-organizing maps) and selection algorithms (Max Diss Algorithm, MDA). The MDA selects a reduced number of multivariate sea states uniformly distributed over data, covering the edges, which results very convenient for a later interpolation. The dynamical downscaling is carried out using different nested state-of-the-art wave propagation models, increasing the spatial resolution near the coast. A multidimensional interpolation scheme based on radial basis functions is used to obtain quantitatively valid time series of wave climate at coastal areas, which are validated numerically and using instrumental data (for reanalysis data bases).

Wave climate projections in the NW Mediterranean

M. Casas-Prat and J.P. Sierra
Universitata Politecnica de Catalunya, Spain

Climate change has become an important issue in the coastal engineering field. The sea level rise is not the only concern but also variations in the wave climate can be expected due to changing wind patterns, affecting the littoral dynamics.

In the European context, the ENSEMBLES project has provided the researching community with daily mean and maximum atmospheric fields (wind, pressure, etc.) at 25 km spatial scale for the continuous time period 1960-2050/2100 using the midline A1B greenhouse scenario. This database represents a useful tool for regional wave modelling of future scenarios. However, such a low time resolution considerably smoothes the resulting wave climate and several peak events are not properly caught.

The present study aims to improve the present knowledge of the tendencies in the wave heights approaching the Catalan coast, situated in the NW Mediterranean sea, which nowadays already has a high percentage of the coast being eroded. For this purpose, two 20-year scenarios are computed: the reference situation (1991-2010) and the future scenario (2081-2100), with a spatial resolution of 1/8º. The forcing input consists of 3-hourly wind fields obtained by Koninklijk Nederlands Meteorologisch Instituut, which used the Regional Circulation Model (RCM) RACMO2 and the Global Circulation Model (GCM) ECHAM5, and the A1B scenario. Therefore, this study correspond to a first attempt because it only considers one RCM-GCM combination instead of ensambling various climatic models.

First results show a tendency of the significant wave height to decrease but a significant change in the annual pattern is obtained. In some areas, higher values are expected during spring and summer seasons, specially for the extreme regime.

Present and future wave climate analysis along the French mainland Atlantic coast, using wave dynamical downscaling

Elodie Charles, Déborah Idier, Rodrigo Pedreros, Gonéri Le Cozannet, Jérôme Thiebot, Fabrice Ardhuin, Serge Planton
BRGM, Service RNSC, 3 av. C. Guillemin, BP 6009, 45060 Orléans cedex 2, France.
e.charles@brgm.fr, d.idier@brgm.fr, r.pedreros@brgm.fr, g.lecozannet@brgm.fr
Ifremer, Centre de Brest, 29280 Plouzané, France.
fabrice.ardhuin@ifremer.fr
Centre National de Recherches Météorologiques, 42 av. G. Coriolis, 31057 Toulouse cedex 1, France.
serge.planton@meteo.fr

Change in ocean wave climate has many implications regarding offshore and coastal hazards. Therefore, knowledge of past and future wave conditions is essential. This study focuses on the Bay of Biscay and more particularly on the French mainland Atlantic coast, where datasets of wave conditions (buoys, modelling) do not provide sufficient long-term and high resolution information for studying past and future wave climate along the Aquitanian coast (France).

A dynamical downscaling approach is then applied to convert available global wind fields into nearshore wave conditions. Waves are generated and propagated all over the North Atlantic Ocean (spatial resolution 0.5°) to the Aquitanian coast (spatial resolution 1 km) using the WAVEWATCH III (NOAA/NCEP) model and the SWAN model. Forced by the ERA-40 reanalysis wind fields (1.125° grid, every 6 hours, from 1958 to 2001), this wave modelling system is calibrated and validated against eleven oceanic and coastal buoys measurements.

Offshore and nearshore wave fields provided from 1958 to 2001 (generated by ERA-40 wind fields) are analysed in terms of multi-decadal trends and inter-annual variability. Concerning future wave climate, the RETIC simulations, performed by ARPEGE model, provide wind fields for a present control period and three emissions scenarios (A1B, A2 and B1). Potential future wave climates are modelled, using these wind fields with the above system. The comparison of the Bay of Biscay wave fields for different emissions scenarios and regarding the present wave climate will be used to evaluate the potential impact of the climate change on the French mainland Atlantic coast.

Acknowledgements: AXA Research Fund for financial funding; ERA-40, CELM, CETMEF, CNRM for providing data; GENCI (Grand Equipement National de Calcul Intensif) for the access to the HPC resources of CINES under the allocation 2010-[c2010016403]; Pascale Delecluse, Michel Déqué and Alain Braun for their advice and help.

Dynamical downscaling of regional wave climate in the northern North Atlantic; results and challenges.

Jens Debernard and Lars Petter Røed
Norwegian Meteorological Institute, Norway

We discuss possible changes in regional wave climate in the northern North Atlantic and adjacent seas found based on two dynamical downscaling studies using input from four different global models and 3 green house gas scenarios. In general, changes in significant wave height in this region are found to be mostly small and insignificant. However, there are some notable exceptions in certain regions. Moreover, there is a tendency for an increase in the most extreme wave events in the warmer period, compared with the present day control climate. An interesting finding is that, the differences between the resulting changes from the various global models, are larger than the resulting changes found from application of different greenhouse gas emission scenarios using the same global model. Furthermore, the studies show that even applying quite large atmospheric downscaling domains does not diminish the large differences in the present day regional wind climate between simulations driven with different global models. We conclude therefore that the change is due to the differences in the global driving climate. In addition, biases in the storm tracks and general circulation given by the global model strongly influence the regional control and scenario climate for the wave height and wave direction.

Simulated wave climatology during the past 30-years and wave climate projection in the late 21st century

Yalin Fan, Shian-Jiann Lin, and Isaac Held
NOAA / GFDL

Ocean surface wave climate change is one of the eight main climate drivers affecting the coast (Hemer, et al 2010). In recent years, several dynamic projections of regional wave climate have been carried out, where downscaled Atmosphere/Ocean Global Climate Model (GCM) projections are used to force regional wave models. But bias could arise in the simulated wave climate from the low level of confidence in the projected circulation changes from GCMs. The European Centre for Medium-Rage Weather Forecasts (ECMWF) ERA-40 reanalysis (T159) produced global wave information at 1.5° resolution. Even though it captures the variability of the true wave height very well on all time scales, due to the relatively coarse resolution of the atmospheric model and its limited ability to resolve storm systems, high wave heights were severely underestimated (Hemer, 2010).
We have developed a high resolution global simulation system by coupling the operational wave model developed at the National Centers for Environmental Prediction/Environmental Modeling Center, to GFDL's prototype Global Cloud-Resolving Model (HiRAM). We have evaluated the performance of this coupled system through climate SST run at 0.5-degree resolution, which shows consistent results with the European center for Medium-Range Weather Forecast (ECMWF). The comparison of wave climate from this run with ECMWF re-analysis is in progress and will be presented at the conference. A 30-year (1980 to 2010) AMIP type wave climate (including wave height, length, direction, peak period, etc) will be generated and the wave climate change during this period will be discussed. The same model will also be used to simulate the wave climate change to the SST/sea ice anomalies in the late 21st century generated by coupled models in the World Climate Research Program Coupled Model Intercomparison Project 3 (CMIP3) archive for IPCC/AR4.

Two-way Coupling between Surface Gravity Waves and Climate

B. Fox-Kemper, A. Webb, L. Van Roekel, G. Danabasoglu, W. G. Large,
and S. Peacock.
University of Colorado, Boulder

Results demonstrating the importance of surface gravity wave effects on global climate models will be presented, and a model-based assessment of the impact of climate change on production of these waves as well. Presently, the surface gravity wave field is not an explicit component of most global climate models. However, mixing by wave-driven turbulence (Langmuir turbulence) has the potential to
dramatically reduce certain climate model biases in the near surface ocean. Including other wave effects promises to reduce other climate model biases. A description of some uncertainties and capabilities of present global modeling and observation of the surface gravity wave field parameters will be presented, along with an assessment of whether these uncertainties outweigh typical variability in the wave field. The expected magnitude of changes due to the seasonal cycle and climate change, and whether these may be reliably modeled will be used to demonstrate degree of feasibility. Finally, preliminary results incorporating the NOAA WaveWatch-III model as a component of the NCAR Community Earth System model, allowing for a two-way coupling of wave effects and climate, will be presented.

A strategy for the regional projections of wind waves using winds from climate model simulation refined with high resolution non-hydrostatic atmospheric model

Alexander Gavrikov, Sergey Gulev and Vika Grigorieva
IORAS, Moscow, gul@sail.msk.ru

Wave parameters are not directly computed by the coupled climate models in present climate simulations and in scenario runs. Instead, wave characteristics can be hindcasted offline using winds from climate model runs as a forcing function for the numerical experimentation with wave models, or statistical methodologies. In both cases, simulated projected waves will be largely dependent on winds whose relatively coarse resolution does not allow to exploit wave model potential to a full extent. For regional scale, especially in the areas where local wind effects might be critical for the adequate representation of wave fields, high resolution hindcasting of winds using present day mesoscale prognostic systems gives a good prospect for establishing more truth in projected waves. We demonstrate this potential for the areas of Barents sea using Weather Research and Forecasting (WRF) model in horizontal resolutions from 12 to 6 kilometers and lateral boundary conditions from selected AR4 models for the present climate simulations and scenario runs during 21st century. Simulated winds over the area of 2000 by 2000 km were then used to force WAVEWATCH model to hindcast local wave parameters. This approach is particularly effective for simulation of strongly constrained by extreme winds wave extremes in climate records and providing more accurate estimates of the occurrence of extreme waves and winds in the future climate.

Preference: oral/poster

Contact: Sergey Gulev, IORAS, 36 Nakhimovsky ave., 119997 Moscow Russia
Phone: +7-499-1247985, email: gul@sail.msk.ru

North Sea wave climate projections for anthropogenic future climate change: an ensemble study

Iris Grabemann, Nikolaus Groll and Ralf Weisse
Helmholtz-Zentrum Geesthacht Center for Materials and Coastal Research, Institute for Coastal Research, Geesthacht, Germany

Anthropogenic climate change may cause long-term changes in wind, wave and storm surge conditions of the North Sea which could have significant impacts on coastal and offshore activities. To estimate possible future changes in the North Sea wave conditions, the effects of an ensemble of eight future climate projections are analysed. This ensemble consists of four transient projections (2001-2100) reflecting the IPCC emission scenarios A1B and B1 and two different initial states, and of four time slice projections (2071- 2100) including the emission scenarios A2 and B2 and two different global climate models. Regionalised
wind fields from the global climate simulations are used to force the spectral wave model WAM for the North Sea. The potential changes in wave conditions are studied by comparing future statistics with the corresponding reference conditions (1961-1990 or 2000).
While for large parts of the North Sea area the severe significant wave heights show an increase towards the end of this century, there are large uncertainties in the magnitude and the spatial patterns of the climate change signals between the eight climate projections. Additionally, the climate signals display strong temporal variations in magnitude and patterns on decadal time scales within and between the four transient projections. For coastal activities especially the synchronous occurrence of severe waves and storm surges is crucial. Using similar future projections for storm surge changes in the North Sea, the joint frequency
distribution of storm surge and wave heights is analysed. Special emphasis is given to the discussion of uncertainties due to scenarios, global climate models and natural variability which should be taken into account in climate impact research.

130 years of visual wind wave observations from VOS (1880-2009): observed climate variability in mean and extreme wave characteristics

Sergey Gulev and Vika Grigorieva
IORAS, Moscow, gul@sail.msk.ru

Voluntary observing ship (VOS) data provide the longest global time series of wind wave characteristics, such as wave heights (prior the late 1950s) and heights, periods and directions of wind sea and swell (starting from the late 1950s). These data form the basis for the regularly updated global wind wave climatology maintained at IORAS. We present the results of the analysis of centennial-scale climate variability of mean and extreme SWH from 1880 onwards. Time dependent biases associated with inadequate sampling were homogenized and the trends and interdecadal changes are considered to be free of artifacts. During the last 130 years our analysis identified upward changes in the mean wave height over North Pacific (up to 7 cm/decade) and the absence of significant linear trends in the North Atlantic. However, after 1950 waves are growing up over Northern Hemisphere mid latitudes showing the strongest increase in the North Atlantic of 12 cm/decade. Extreme waves were estimated from initial value distribution and using peak over threshold methods. In order to apply extreme value statistics to heavily and inhomogeneously undersampled VOS data, we used 6-hourly snapshots of wave characteristics from ERA-40-WAM hindcast covering the period from 1958 to 2002. These model data were subsampled in order to simulate VOS sampling density. We found statitically significant changes in wave extremes, implying growing tendency in both Atlantic and Pacific. Interestingly, for the last 5-6 decades in the Pacific changes in extreme SWH are clearly coordinted with the increase of extreme seas, while in the North Atlantic changes in extreme SWH do not show correlation with extremes in wind sea, but rather linked to the changes in swell. For the period after 1970 our analysis also includes wave periods and directions. Secular increase of wind sea periods in both Northern and Southern Hemispheres is not, however proportional to the changes in wind sea heights, implying statistically significant trend in the wind sea steepness. Furthermore, data for the last 40 years clearly show that extreme waves become more steep for most areas. Results of the analysis of visual VOS data provide the ground for extensive validation of model hindcasts of wave parameters using state of the art wave modelling platforms and forcing functions from reanalyses and climate models.

Coordinated global wave climate projections.

M.A. Hemer[1], J.A. Church[1], V.R. Swail[2] and X.L. Wang[2].
[1] Centre for Australian Weather and Climate Research: A partnership between the Bureau of Meteorology and CSIRO Marine and Atmospheric Research
Hobart, Tas 7001, Australia
[2] Climate Research Division, Science and Technology Branch, Environment Canada, Toronto, Canada.

Future changes in surface ocean wave conditions received only minimal attention in the IPCC AR4, despite recognition that wave heights have altered over large portions of the global ocean through the historical record. WG-2 identified waves as one of eight main climate drivers affecting the coast, yet WG-1 indicated that the limiting factor in making assessments of the effects of climate change on coastal erosion is insufficient projections of wave conditions. Beyond the coastal zone, potential future ocean wave changes will have important implications for many offshore applications.

In recent years, several regional wave climate projections have been carried out, where surface forcing/covariates are produced by regional climate models which have been used to downscale global climate model scenarios. Many of these models have repeated effort, downscaling identical GCM for the same emission scenarios (using different regional models).

Given substantial uncertainty exists in projected circulation patterns from available GCM's, increased confidence in projections requires runs over an increased number of run ensembles (altered GCM, altered SRES and ensembles of each set).

Increasingly more regions are interested in surface ocean wave climate projections. The current regional approach dictates considerable repeated effort, so we advocate a shift to global projections (statistical and dynamical). This comes at substantial computational cost, which can be countered by interested parties participating in a coordinated approach (along the lines of the CMIP experiments), whereby individual research groups carry out global projections for selected scenarios. When combined with results from other groups, a distribution of projections will be available to increase statistical certainty. Once global projections are established, downscaling methods may be applied to obtain sufficient information for regional assessments. The proposed CMIP5 experimental design allows global projections of wave climate, in a manner resembling the prior regional assessments, focussing on mid and end of 21st century time-slices.

Projected future wave climate along Australia's eastern margin

Mark Hemer[1], Jack Katzfey[1], Kathleen McInnes[1] and Rosh Ranasinghe[2]
[1]CAWCR-CSIRO, Australia
[2] UNESCO IHE and TU Delft, The Netherlands

This paper explores three sources of uncertainty in dynamical wave climate projections on both regional (East Australian) and global domains. In each case, the WAVEWATCH III spectral wave model is forced with climate model derived surface winds and ice concentrations for a present 20-yr time-slice (1981-2000) and a projected future 20-yr time-slice (2091-2100).

The first level of uncertainty in future climate projections is the way the climate will respond to greenhouse gas concentrations, which is often assessed through the comparison of different GCM model responses to a particular emission scenario. To explore this level of uncertainty, a 3-member ensemble where CSIRO's stretched grid downscaling model (CCAM) has been used to dynamically downscale three different CMIP-3 GCM's (CSIRO Mk3.5, GFDLcm2.0 and GFDLcm2.1) is considered.

The second of these uncertainties is the uncertainty in the future emissions of greenhouse gases, which is addressed in the wave model simulations by applying wind forcing from the CCAM simulations forced with plausible future scenarios of greenhouse gas emissions (SRES A2 and B1), for each of the 3-member ensemble.

The third level of uncertainty surrounds how biases in forcing wind data (which were found between CCAM downscaled GCM winds and observational/reanalysis winds) are treated. Three different methods of applying wind forcing to wave models to develop future wave climate projections were tested. 1. Forcing the model with un-adjusted climate model winds, 2. Bias-adjusting climate model surface winds to account for both climate and variability bias to more closely represent reanalysis winds, and in turn force the wave model, and 3. Perturb the observed (reanalysis) present climate wind field by the difference between the present and projected climate model wind field, to force the wave model.

This limited but not exhaustive investigation of three contributions to uncertainty in projected regional east Australian wave climate has found that the different method of applying winds from a climate model to the wave model introduce the largest uncertainty in the final results. Investigations of these same three contributions of uncertainty to global wave climate projections are currently underway, where downscaled CCAM surface winds are being used to force a 1 degree global implementation of WAVEWATCH III for two 30-yr time-slices (1979-2009 – to align with the NCEP CFSR, and 2070-2099). Preliminary results will be presented at the workshop.

Statistical downscaling of extreme wave climate

Cristina Izaguirre, Paula Camus, Melisa Menendez, Fernando J. Mendez, Iñigo J. Losada

Environmental Hydraulics Institute "IH Cantabria", Universidad de Cantabria, Spain

It is well known nowadays that the seasonal-to-interannual variability of wave climate is linked to the anomalies of the atmosphere circulation. In this work, we propose an extreme value model for extreme significant wave height at a particular site (predictand) conditioned to the synoptic-scale weather type (predictor). We combine different state-of-the-art extreme value models based on the Generalized Extreme Value (GEV) for block maxima and the Poisson-Pareto model for exceedances over a threshold and clustering techniques (self-organizing maps, K-means) applied to n-days-averaged sea level pressure field (SLP) anomalies to describe weather types.

We fit the statistical model using as predictor the n-days-averaged SLP fields calculated by NCEP atmospheric reanalysis (1948-2010) and as predictand is the distribution of maxima every n-days in a specific location of the GOW1.0 calibrated wave reanalysis of IH Cantabria. The spatial and temporal domain of the predictor is chosen by means of a sensitivity analysis and based on physical criteria. We analyze the suitability of this methodology to be used for long-term projection of extreme wave climate to different climate change scenarios.

Numerical Study of Wind Wave Climatology over the Northwestern Pacific Ocean using Operational Ocean Forecasting System in KMA

KiRyong Kang, WooJeong Lee, Jong Suk Park, Sung Hyup You and Sang-Boom Ryoo
Korea Meteorological Administation, Seoul, 156-720, Korea
E-mail : krkang@kma.go.kr,

Understanding the long-term change of the wave environment including the extreme wave case will be helpful for the operational wave field, for planning of coastal structures and especially mitigation of ocean hazards. The Northwestern Pacific Ocean is one of the active areas in the world with severe impacts of tropical cyclones. In this study we investigated the long-term trend of wave height of the Northwestern Pacific Ocean for 40 years (1960 – 2000) in terms of the spatial and temporal variation using the Korea Meteorological Administration (KMA)'s operational wave forecasting system which is based on the third generation wave model called the WAVEWATCH III (WW3). The wind data, as a forcing term to generate the wave in the ocean, was produced by the Climate Data Assimilation System (CDAS) of the National Centers for Environmental Prediction.

The simulated wave climatology is basically compared with global ECMWF ERA40 wave reanalysis data. A difference was shown at the distribution of the maximum wave height indicating the higher maximum wave vale displayed around East China Sea. From the EOF analysis of wave height, the contribution of the 1st, 2nd and 3rd component were 35.6%, 16.9%, and 12.81%, respectively. The first component's eigen vector was maximum around 25°N, 135°E and gradually decreased into coast area, and second component divided into two areas centered at the cross line of the main axis of Kuroshio Current by the opposite sign of the eigen vectors. In the decadal mean distribution, it showed some increase trend in wave height compared to the values of 1960s, and it was winter season that the highest increase existed below 30°N in terms of seasonal variation. However it also showed a decreased pattern around Korean peninsula during the winter. These indicate that the wave environment could change differently region by region in terms of the long-term atmospheric condition.

Keywords: wave climatology, wave forecasting system, WAVEWATCH III, EOF

Regional wave climate projection studies in the Mediterranean Sea

P.Lionello
Univ. of Salento and CMCC, Italy

In the Mediterranean Sea to identify changes of the wave fields produced by future emission scenarios is important because of their action on its long coastlines (46,000 km) and their relevance for the intense ship traffic (with both a commercial and touristic component) in this basin.

This contribution discusses the reliability of model simulations of wave climate in the Mediterranean Sea by comparing the last part of a 44 -year long hindcast study with observations and presents the results of climate scenario simulations. It is shown that simulations reproduce adequately the characteristics of the monthly average fields, though with some limitations in reproducing the variability of extremes. The analysis of a model simulation, based on the wind fields of the RegCM regional climate model, suggests milder marine storms and wave conditions in future climate scenarios for both average and extreme values in winter, spring, and autumn, while in summer in some areas mean and extreme SWH becomes higher. Most changes appear to increase with the emission level and some of them are consistent with present climate trends.

Dynamic Projection of Future Wave Climate Change in Global Scale

Nobuhito Mori, Tomoya Shimura, Tomohiro Yasuda and Hajime Mase
Disaster Prevention Research Institute, Kyoto University, Japan

The influence of global climate change due to green house effects on the earth environment will require impact assessment, mitigation and adaptation strategies for the future of our society. This study directly predicts future ocean wave climate in comparison with present wave climate based on the atmospheric general circulation model and global spectral wave model. The future change of annual averaged and extreme sea surface winds and waves are analyzed in detail. There are clear regional dependence of both annual average and also extreme wave height changes from present to future climates. Although, the future wave period change is negligible, the wave direction change will be significant in the middle latitude. Detail of analysis will be presented at the conference.

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On the relevance of time and spatial variability of long term wave hindcast on energy resources evaluation and its potential implications onto wave climate projection uncertainties.

F. J. Ocampo-Torres and the Waves Group at CICESE
Department of Physical Oceanography, CICESE, Ensenada BC 22860 Mexico

Making use of long-term numerical simulation and short-period in situ records of the wave field, time and spatial variability of the most important wave characteristics has been assessed in order to determine its impact on the estimation of energy potentially available. The area of interest is the Pacific coastal region off the Baja California peninsula in Mexico.

Implementing a third generation spectral wave model over practically the whole Pacific Ocean, using NCEP surface wind re-analysis as forcing fields, hindcast results are obtained for oceanic scale runs (1 x 1 degree resolution). Smaller scale and finer resolution results are obtained after nesting the SWAN model in the coastal region.

An important issue is the wide range of frequencies resolved by the models in order to better reproduce relevant processes in coastal regions such as non-linear interactions and changes in the directional spreading of the wave spectrum.

A detailed analysis of time variability of the wave field is performed and the potential impact on the estimation of extreme values is assessed. Long term tendencies of wave parameters are discussed within the context of local and coastal behaviour of the wave phenomenon, while its potential impact on wave climate projections are also addressed.

Response of extreme waves to variations in regional North Atlantic climate

Will Perrie, Lanli Guo, Bash Toulany, Zhenxia Long
Bedford Institute of Oceanography, Canada

Winds are always of key importance in any study of ocean waves. To consider the impacts of climate variability, we do dynamical downscaling to simulate winds related to extra-tropical cyclones in the Northwest Atlantic, and consider the variability of cyclone climatology, and the impacts of climate change following accepted IPCC scenarios. Two methodologies are attempted. In one approach (Jiang and Perrie, 2007, 2008) a mesoscale atmospheric model is used to simulate ensembles of cyclone winds. In this methodology, we also considered the influence of atmosphere-ocean two-way coupled dynamics, on storm intensity (which can reduce 10-m winds by as much as 2–4 m/s) and on storm tracks (Yao et al., 2008; Perrie et al., 2010); the impact of climate change is seen in slightly decreased intensities in landfalling cyclones (~5 hPa) resulting from the competition between climate change warming and modest cooling near the storm center induced by dynamic cooling, and slight northward shift in cyclone tracks. Storms with trajectories that move close to the upper level steering jet exhibit the largest change in tracks, moving closer to the North American coast (Jiang and Perrie, 2008). In an alternate approach, (Long et al., 2010, Perrie et al., 2011) a relatively fine-resolution regional climate model is used to simulate cyclones and their climatology, in this simulations up to ~ century timescales. In this presentation, we focus on the latter methodology. For present climate, the integration was performed for 1970-1999; results give a relatively accurate description of marine winds and surface air temperature. Winds are used to drive a modern state-of-the-art wave model WaveWatchIII (WW3) version 3.14, using mosaic-grid two-coupled fine-coarse mesh grids to estimate climate effects on waters off eastern Canada. EOF analysis is used to show that decreases (increases) in highest significant wave heights for each autumn-storm season correspond to decreases (increases) in extra-tropical cyclone activity in the Northwest Atlantic.

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The influence of atmosphere-ocean-wave coupling, wave drag and sea spray on ocean waves in midlatitude storms

Will Perrie, Weiqing Zhang, Lanli Guo, Bash Toulany
Bedford Institute of Oceanography, Canada

A coupled atmosphere – wave – sea spray model system is used to evaluate the impacts of sea spray and wave drag on storm-generated significant wave height (Hs), wind-wave directional variations, and directional wave spectra related to the storm location and translation speed. Although the sea state may be complex, results suggest that the decrease/increase of Hs due to wave spray and wave drag is most significant in high wind regions to the right of the storm track. Because of the additional effect of storm translation speed, particularly when the storm moves in the same direction as the local wind, maximum wave heights tend to occur several hours after the peak wind events. Moreover, the directional misalignment between local winds and propagating waves, within rapidly moving winter storms, can be a great and highly variable effect, in relation to the location of the storm centre. The spatial variation of the directional wave spectra is closely related to the relative position of the storm center, and depends on the location of the radius of maximum winds, and the storm translation speed. While wave-drag and sea spray can reduce or increase the magnitudes of wind and Hs, respectively, they have little apparent effect on the directional wave spectra, as their parameterizations have thus far not included dependence on directional seastate.

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Impact of a Warmer Climate on the Global Wave Field
Preliminary Results

Alvaro Semedo
Escola Naval-CINA, Lisbon, Portugal, and Uppsala University, Sweden
Arno Beherens
Helmholtz-Zentrum Geesthacht, Center for Materials and Coastal Research, Germany
Lennart Bengtsson
National Centre for Earth Observation, University of Reading, Whiteknights, Reading, United Kingdom, and Max Planck Institute for Meteorology, Hamburg, Germany
Heinz Gunter
Helmholtz-Zentrum Geesthacht, Center for Materials and Coastal Research, Germany
Andreas Sterl
Royal Netherlands Meteorological Institute (KNMI), De Bilt, Netherlands
Ralf Weisse
Helmholtz-Zentrum Geesthacht, Center for Materials and Coastal Research, Germany

The details of the evolution of the global wave climate and its change in a changing climate received minimal attention in the IPCC Fourth Assessment Report (AR4). It is restricted to the long term variability of the significant wave height parameter, based on visual estimates from voluntary observing ships, ignoring other wave parameters. Despite some attempts in studying the impact of a warmer climate in the global wave field based on statistical projections, and some recent regional dynamical projections using regional climate models to force wave models, a coherent global modeling study of the future changes in the global wave climate is still lacking.
The extratropical cyclones are the main generating force behind the global wave field. Recent studies, based on runs with the high resolution (T213; 63 km) version of the ECHAM5 global climate model revealed that in a warmer climate extratropical storms will not necessarily get more intense. On the other hand a poleward shift on the extratropical storm tracks is expected in both hemispheres. The effects of these changes on the future global wave climate are investigated in the present study. The high resolution ECHAM5 10 m winds are used to force the wave model WAM and simulate the global wave climate of two 32-yr periods that are representative of the end of the twentieth (1959-1990) and twenty-first (2069-2100) centuries. The twentieth century period is the control period. The significant wave heights from the control period are compared with the ECMWF reanalysis ERA-40 for verification, and, for the short overlapping period (1989-1990), also with ERA-Interim. Preliminary results of the impact of a warmer climate at the end of the twenty-first century on the global significant wave height field are presented.

Statistical reconstruction and projection of ocean waves

Xiaolan L. Wang, Val R. Swail, and Yang Feng
Climate Research Division, Science and Technology Branch, Environment Canada, Toronto, Canada

This presentation is about using statistical methods to represent the relationship between ocean wave variables (significant wave height; may also include wave period and direction) and some closely related atmospheric predictors (such as those derived from the sea level pressure fields), and then using the relationship to reconstruct ocean wave conditions in the past century and to project possible future changes in ocean waves. First, the ERA40 reanalysis of SLP and ocean wave variables are used to calibrate the statistical relationships. Then, SLP data from the newly completed 20th Century Reanalysis (20CRv2) are used to reconstruct ocean wave conditions in the period from 1871-2008 (138 years) and to infer historical changes in global waves. The CMIP5 simulations of the present and possible future climates will also be used to project possible ocean wave changes in the 21st century.

Regional wave climate simulations at the Helmholtz-Zentrum Geestacht, Institute for Coastal Research

Ralf Weisse, Heinz Günther, Iris Grabemann, Nikolaus Groll and Birgit Hünicke

Helmholtz-Zentrum Geesthacht, Center for Materials and Coastal Research, Institute for Coastal Research, Geesthacht, Germany

Studies on wave climate and wave climate changes have received increasing attention within the last few years. Among the reasons are the limited number of long-term observational measurements in combination with increasing interest from offshore industry and coastal protection management. Potential future changes in wave climate are of similar importance but from the global perspective the number of studies so far remains limited.

Here we present an overview of past and ongoing activities at our Institute to simulate and analyse changes in regional wave climate. This comprises both, studies about recent changes (multi-decadal hindcasts) and potential future changes (climate change projections). So far, studies are regionally limited. Examples from the North Sea and the Baltic Sea are provided.

While high-resolution regional studies are needed and are essential for regional planning and activities global studies on wave climate and wave climate changes are needed to obtain a large-scale picture and to provide the boundary conditions for regional simulations for exposed areas. We intend to provide a number of such global simulations that may substantially contribute to the workshop objectives.

The wave climate of the NW European Continental Shelf

Judith Wolf and Lucy Bricheno

National Oceanographic Centre, Liverpool, UK.

Over recent years various studies of the wave climate of the NW European continental shelf have been made using wave models validated against wave observations. Model runs include 10 year hindcast from 1999-2008 and projections of future wave climate around the UK driven by winds from a subset of the Met Office/Hadley Centre climate model ensemble members. The wave model which is used is based on the well-tested 3rd-generation spectral model WAM implemented on two grids: a coarse 1° grid for the Atlantic to provide boundary conditions, and a 12km model of the NW European continental shelf. The WAM model has been well-validated previously and is shown to be in reasonable agreement with observations for the hindcast runs and statistically in reasonable agreement with the ERA-40 reanalysis for the NE Atlantic. Seasonal mean and extreme waves are generally expected to increase to the SW of UK, reduce to the north of the UK and experience little change in the southern North Sea. There are large uncertainties especially with the projected extreme values. A detailed study of Liverpool Bay has been made using wave buoys and acoustic instruments within the footprint of a phased-array HF radar system (measuring currents and waves), as part of the NOC Irish Sea Observatory. Several years of data have been collected and are supplemented by an 11-year wave model hindcast. The variation of wave climate over various time-scales from seasonal and inter-annual to inter-decadal is examined, using various statistics, including extreme value methods. Projections of 50-year return period wave heights differ between different instruments and model datasets. The future wave climate of Liverpool Bay is not expected to change much from the present day. There is evidence for variability on decadal time-scales, with some correlation with the North Atlantic Oscillation, thus future extreme wave events will be closely related to future North Atlantic storm tracks.

Annex 4

Acronyms and Other Abbreviations and Symbols

ACCESS	Australian Community Climate Earth-System Simulator
CESM	Community Earth System Model
CIRES	Cooperative Institute for Research in Environmental Sciences (University of Colorado)
CMIP	Coupled Model Intercomparison Project
COASTALT	Development of Radar Altimetry Data Processing in the Coastal Zone (ESA Project)
COWCLIP	Coordinated Ocean Wave Climate Projections
ECMWF	European Centre for Medium-Range Weather Forecasts
GFDL	Geophysical Fluid Dynamics Laboratory (USA)
IOC	Intergovernmental Oceanographic Commission (of UNESCO)
IPCC	Intergovernmental Panel on Climate Change
JCOMM	Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology
MSLP	Mean Sea Level Pressure
NCSFR	NOAA Climate Forecast System Reanalysis
NOAA	National Oceanic and Atmospheric Administration (USA)
NAO	North Atlantic Oscillation
VOS	Voluntary Observing Ship
WCRP	World Climate Research Programme
WGCM	Working Group on Coupled Modelling
WMO	World Meteorological Organization

New JCOMM series replaces discontinued MMROA series

JOINT WMO/IOC TECHNICAL COMMISSION FOR OCEANOGRAPHY AND MARINE METEOROLOGY TECHNICAL REPORT SERIES

No.	Title	WMO/TD-No.	Issued
55	WCRP-JCOMM Workshop on Coordinated Global Wave Climate Projections – ***Website only***	WMO/TD-No. 1518	2011
54	Ship Observations Team (SOS) Annual Report 2010	WMO/TD-No. 1568	2011
53	The WMO-IOC Network of Regional Marine Instrument Centres (RMICS)	WMO/TD-No. 1564	2010
52	11th international workshop on wave hindcasting and forecasting and 2nd coastal hazard symposium Halifax, Canada, 18-23 October, 2009.	WMO/TD-No. 1533	2010
51	SOT Annual Report for 2009	WMO/TD-No.	2009
50	JCOMM-III – Scientific Lectures – ***Website only***	WMO/TD-No. 1518	2009
49	Proceedings of the 2nd Ice Analysts Workshop, Rostock, Norway 15-19 June 2009 – ***Website only***	WMO/TD-No. 1517	2009
48	Pilot Project for the Integration of marine meteorological and other appropriate oceanographic observations into the WMO Integrated Global Observing System (WIGOS) (WIGOS Pilot Project V - JCOMM Pilot Project for WIGOS)	WMO/TD-No. 1515	2009
47	JCOMM Technical Workshop on Wave Measurements from Buoys, 2-3 October 2008, New York City, USA	WMO/TD-No. 1466	2008
46	SOT Annual Report for 2008	WMO/TD-No. 1459	2008
45	Proceedings of the 3rd JCOMM Workshop on Advances in Marine Climatology, Gdynia, Poland, 6-9 May 2008	WMO/TD-No. 1445	2008
44	Proceedings of **1)** 1st JCOMM Scientific & Technical Symposium on Storm Surges, Seoul, Korea 2-6 Oct. 2007	WMO/TD-No. 1442	2008

No.	Title	WMO/TD-No.	Issued
	2) 10th International Workshop on Wave Hindcasting & Forecasting & Coastal Hazard Symposium , North Shore Oahu, Hawaii, 11-16 November 2007 – ***CD ROM***		
43	Proceedings of the Ice Analysts Workshop, Rostock, Germany 12-17 June 2008 – ***CD ROM***	WMO/TD-No. 1441	2008
42	Proceedings of the OGP/JCOMM/WCRP Workshop on Climate Change & the Offshore Industry Geneva, 27-29 May 2008 – ***CD ROM***	WMO/TD-No. 1440	2008
41	SOT Annual report for 2007	WMO/TD-No. 1431	2008
40	JCOMM Data Management Plan	WMO/TD-No. 1426	2008
39	JCOMM Expert Team on Marine Accident Emergency Support (ETMAES), First Session - National Reports (Angra dos Reis, Brazil, 29-31 January 2007) - **Website only**	WMO/TD-No. 1399	2007
38	JCOMM Expert Team on Maritime Safety Services (ETMSS), Second Session - National Reports (Angra dos Reis, Brazil, 24-27 January 2007) - **Website only**	WMO/TD-No. 1398	2007
37	Application of collected data, Presentations at the DBCP Technical Workshop, Buenos Aires, Argentina, 17-18 October 2005 – ***WEB ONLY***	WMO/TD-No. 1388	2006
36	SOT Annual report for 2006	WMO/TD-No. 1394	2007
35	Application of collected data, Presentations at the DBCP Technical Workshop, Chennai, India, 18-19 October 2004 – ***WEB ONLY***	WMO/TD-No. 1387	2006
34	Ninth International Workshop on Wave Hindcasting and Forecasting (Victoria, Canada, 24-29 September 2006) – ***CD ROM***	WMO-TD. No. 1368	2007
33	Techniques and Benefits of Satellite Data and Wave Models, J.-M. Lefèvre, J.-R. Bidlot and S. Abdalla	WMO/TD-No. 1357	2006
32	SOT annual report for 2005 – ***CD ROM***	WMO/TD-No. 1346	2006
31	Manual on Sea Level, Measurement and Interpretation, Volume IV: An Update to 2006	WMO/TD-No. 1339	2006
30	Verification of Operational Global and Regional Wave Forecasting Systems against Measurements from Moored Buoys, by J.-R. Bidlot and M.W. Holt	WMO/TD-No. 1333	2006
29	Eighth International Workshop on Wave Hindcasting and Forecasting (North Shore, Oahu, Hawaii, 14-19 November 2004)	WMO/TD-No. 1319	2006
28	Third International Workshop for Port Meteorological Officers (Hamburg, Germany,	WMO/TD-No. 1318	2006

No.	Title	WMO/TD-No.	Issued
	23-24 March 2006 – ***CD ROM***		
27	An International Seminar to Celebrate the Brussels Maritime Conference of 1853 - An Historical Perspective of Operational Marine Meteorology and Oceanography - Proceedings - ***CD ROM***	WMO/TD-No. 1226	2004
26	Automated Shipboard Aerological Programme (ASAP) - Annual Report for 2003	WMO/TD-No. 1224	2004
25	Second International Workshop for Port Meteorological Officers - ***CD ROM***	WMO/TD-No. 1216	2004
24	Ice Chart Colour Code Standard	WMO/TD-No. 1215	2004
23	SIGRID-3: A Vector Archive Format for Sea Ice Charts	WMO/TD-No. 1214	2004
22	Proceedings of CLIMAR-II - Second JCOMM Workshop on Advances in Marine Climatology (Brussels, Belgium, 17-22 November 2003) - ***CD ROM***	WMO/TD-No. 1199	2004
21	Workshop on Wind Wave and Storm Surge Analysis and Forecasting for Caribbean Countries (Dartmouth, Canada, 16-20 June 2003) - ***CD ROM***	WMO/TD-No. 1171	2003
20	JCOMM Ship Observations Team, Second Session - National Reports (London, United Kingdom, 28 July - 1 August 2003) - **Website only**	WMO/TD-No. 1170	2003
19	Automated Shipboard Aerological Programme (ASAP) - Annual Report for 2002	WMO/TD-No. 1169	2003
18	JCOMM Expert Team on Maritime Safety Services (ETMSS), First Session - National Reports (Lisbon, Portugal, 11-14 September 2002) - **Website only**	WMO/TD-No. 1135	2002
17	JCOMM Ship Observations Team, First Session - National Reports (Goa, India, 25 February - 2 March 2002) - **Website only**	WMO/TD-No. 1121	2002
16	Scientific and Technical Workshop of the JCOMM Ship Observations Team - Presentations at the first session of the Ship Observations Team (Goa, India, 26 February 2002) - ***CD ROM***	WMO/TD-No. 1118	2002
15	Automated Shipboard Aerological Programme (ASAP) - Annual Report for 2001	WMO/TD-No. 1112	2002
14	Operational Oceanography - Scientific Lectures at JCOMM-I (Akureyri, Iceland, June 2001)	WMO/TD-No. 1086	2001
13	Advances in the Applications of Marine	WMO/TD-No. 1081	2003

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	Climatology - The Dynamic Part of the WMO Guide to the Applications of Marine Climatology - ***CD ROM***		
12	Automated Shipboard Aerological Programme (ASAP) – Annual Report for 2000	WMO/TD-No. 1069	2001
11	JCOMM Capacity Building Strategy	WMO/TD-No. 1063	2001
10	Proceedings of CLIMAR99 - WMO Workshop on Advances in Marine Climatology (Vancouver, Canada, 8-15 September 1999) - ***CD ROM***	WMO/TD-No. 1062	2003
9	Estimation of Extreme Wind Wave Heights	WMO/TD-No. 1041	2000
8	Oceanographic and Marine Meteorological Observations in the Polar Regions - A Report to the Joint WMO/IOC Technical Commission on Oceanography and Marine Meteorology	WMO/TD-No. 1032	2000
7*	Proceedings of a Workshop on Mapping and Archiving of Sea Ice Data – The Expanding Role of Radar, Ottawa, Canada, 2-4 May 2000	WMO/TD-No. 1027	2000
6	Automated Shipboard Aerological Programme (ASAP) – Annual Report for 1999	WMO/TD-No. 1011	2000
5	Voluntary Observing Ships (VOS Climate Subset Project (VOSCLIM) – Project Document)	WMO/TD-No. 1010	2000
	Revision 1	WMO/TD-No. 1042	2001
	Revision 2 - **Website only**	WMO/TD-No. 1122	2002
4	The Voluntary Observing Ships Scheme – A Framework Document	WMO/TD-No. 1009	2000
3*	JCOMM Ship-of-opportunity Programme Implementation Panel, Third Session, La Jolla, CA, USA, 28-31 March 2000 – SOOP Status Reports – SOOP Scientific and Technical Developments	WMO/TD-No. 1005	2000
2	Meeting of Experts on a JCOMM/GOOS Polar Region Strategy, Geneva, Switzerland, 6-8 December 1999 - Status Reports from Existing Polar Region Observing Systems	-	2000
1*	First Transition Planning Meeting - St Petersburg, Russian Federation, 19-23 July 1999 – Status Reports from JCOMM Component Bodies and Activities	-	1999

No.	Title	WMO/TD-No.	Issued
44	Marpolser 98 - Metocean Services for Marine Pollution emergency Response Operations, Townsville, Australia, 13-17 July 1998 – Proceedings - Volume 2 - Review and Information Papers	WMO/TD-No. 960	1999
	Marpolser 98 - Metocean Services for Marine Pollution emergency Response Operations, Townsville, Australia, 13-17 July 1998 – Proceedings - Volume 1 - Research Papers	WMO/TD-No. 959	1999
43	Proceedings of the International Workshop on Digitization and Preparation of Historical Marine Data and Metadata, Toledo, Spain, 15-17 September 1997	WMO/TD-No. 957	1999
-	Automated Shipboard Aerological Programme (ASAP) - Annual Report for 1998	WMO/TD-No. 951	1999
42	Provision and Engineering Operational Application of Ocean Wave Data - in French only	WMO/TD-No. 938	1998
41	The Climate of the Baltic Sea Basin	WMO/TD-No. 933	1998
40	Automatisation de l'observation en mer Automation of Observations at Sea	WMO/TD-No. 928	1998
-	Automated Shipboard Aerological Programme (ASAP) - Annual Report for 1997	WMO/TD-No. 900	1998
39	Proceedings of the Commission for Marine Meteorology Technical Conference on Marine Pollution	WMO/TD-No. 890	1998
38	Evaluation of the Highest Wave in a Storm (A.V. Boukhanovsky, L.J. Lopatoukhin, V.E. Ryabinin)	WMO/TD-No. 858	1998
37	Tropical Coastal Winds (W.L. Chang)	WMO/TD-No. 840	1997
36	Handbook of Offshore Forecasting Services (Offshore Weather Panel)	WMO/TD-No. 850	1997
-	Automated Shipboard Aerological Programme (ASAP) - Annual Report for 1996	WMO/TD-No. 819	1997
35	Ice Navigation Conditions in the Southern Ocean (A.A. Romanov)	WMO/TD-No. 783	1996
-	Automated Shipboard Aerological Programme (ASAP) - Annual Report for 1995	WMO/TD-No. 767	1996
34	Polar Orbiting Satellites and Applications to Marine Meteorology and Oceanography – Report of the CMM-IGOSS-IODE Sub-group on Ocean Satellites and Remote Sensing	WMO/TD-No. 763	1996
33	Storm Surges (Vladimir E. Ryabinin, Oleg I. Zilberstein and W. Seifert)	WMO/TD-No. 779	1996

No.	Title	WMO/TD-No.	Issued
32*	Proceedings of the WMO/IOC Workshop on Operational Ocean Monitoring Using Surface Based Radars, Geneva, 6-9 March, 1995	WMO/TD-No. 694	1995
-	Proceedings of the WMO/IOC Technical Conference on Space-based Ocean Observations, September 1993, Bergen, Norway **(US $15.00)**	WMO/TD-No. 649	1994
31*	Proceedings of the International Workshop on Marine Meteorology	WMO/TD-No. 621	1994
30	Proceedings of the International Seminar for Port Meteorological Officers	WMO/TD-No. 584	1993
29	Meteorological Requirements for Wave Modelling (Luigi Cavaleri)	WMO/TD-No. 583	1993
28*	Proceedings of the Commission for Marine Meteorology Technical Conference on Ocean Remote Sensing	WMO/TD-No. 604	1993
27	A Survey on Multidisciplinary Ocean Modelling and Forecasting (Johannes Guddal)	WMO/TD-No. 516	1992
26	The Accuracy of Ship's Meteorological Observations - Results of the VSOP-NA		1991
25	Ships Observing Marine Climate - A Catalogue of the Voluntary Observing Ships Participating in the VSOP-NA	WMO/TD-No. 456	1991
24	Proceedings of the Commission for Marine Meteorology Technical Conference on Ocean Waves	WMO/TD-No. 350	1990
23	Summary Report on National Sea-ice Forecasting Techniques	WMO/TD-No. 329	1989
22	Wind Measurements Reduction to a Standard Level (R.J. Shearman and A.A. Zelenko)	WMO/TD-No. 311	1989
21	Coastal Winds (E.P. Veselov)	WMO/TD-No. 275	1988
20*	La Prévision du Brouillard en Mer (M. Trémant) Forecasting of Fog at Sea - in French only	WMO/TD-No. 211	1987
19	A Global Survey on the Need for and Application of Directional Wave Information (S. Barstow and J. Guddal)	WMO/TD-No. 209	1987
18	Baltic Multilingual List of Sea-ice Terms (Jan Malicki, Alex N. Turchin, Hans H. Valeur)	WMO/TD-No. 160	1987
17	Processing of Marine Data (G.D. Hamilton)	WMO/TD-No. 150	1986
16*	Field Workshop on Intercalibration of Conventional and Remote-sensed Sea Surface Temperature Data (A.E. Strong and E.P. McClain)		1985

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15*	Forecast Techniques for Ice Accretion on Different Types of Marine Structures, Including Ships, Platforms and Coastal Facilities	WMO/TD-No. 70	1985
14	Scientific Lectures at CMM-IX	WMO/TD-No. 41	1985
13	User's Guide to the Data and Summaries of the Historical Sea Surface Temperature Data Project	WMO/TD-No. 36	1985
12	WMO Wave Programme: National Reports for 1984 on Wave Measuring Techniques, Numerical Wave Models and Intercomparisons	WMO/TD-No. 35	1985
*	Supplement No. 4 - Reports for 1991 to 1994 on Wave Measuring Techniques, Numerical Wave Models and Intercomparisons	WMO/TD-No. 35	1994
	Supplement No. 3 - Reports for 1989 to 1990 on Wave Measuring Techniques, Numerical Wave Models and Intercomparisons	WMO/TD-No. 35	1990
	Supplement No. 2 - Reports for 1986 to 1988 on Wave Measuring Techniques, Numerical Wave Models and Intercomparisons	WMO/TD-No. 35	1989
	Supplement No. 1 - Reports for 1985 on Wave Measuring Techniques, Numerical Wave Models and Intercomparisons	WMO/TD-No. 35	1986
11	Drifting Buoys in Support of Marine Meteorological Services (Glenn D. Hamilton)	-	1983
10*	Guide to Data Collection and Services Using Service Argos (revised version)	-	1989
9	Intercalibrations of Directly-measured and Remotely Sensed Marine Observations (Alan E. Strong)	-	1983
8	Summary WMO Technical Conference on Automation of Marine Observations and Data Collection	-	1981
7*	Proceedings of the WMO Technical Conference on the Automation of Marine Observations and Data Collection	-	1981
6	Report on the Results of An Enquiry on Marine Meteorological Services Products	-	1981
5	The Automation of Observational Methods on Board Ship (M. Yasui)	-	1981
4	Intercalibration of Surface-based and Remotely Sensed Data (except Sea Surface Temperature Data) to Be Used in Marine Applications (E.P. McClain)	-	1981
3	Review of Reference Height for and	-	1981

No.	Title	WMO/TD-No.	Issued
	Averaging Time of Surface Wind Measurements at Sea (F.W. Dobson)		
2	Investigation of Contemporary Methods of Measuring Sea Surface and Surface-layer Temperatures (F.S. Terziev)	-	1981
1	Precipitation Measurement at Sea (G. Olbrück)	-	1981