Report from the

Atmosphere-Ocean Interaction Workshop

Bergen, Norway, 12 – 14 April 2010

Organized by the University of Bergen under the auspices of NFR project no. 175763 “Atmosphere-Ocean Interaction”, and the Norwegian Research School in Climate Dynamics (ResClim)

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1. Introduction

A research workshop on atmosphere-ocean interaction was held at the Hotel Augustin in Bergen, Norway, on 12-14 April 2010. The workshop was organized by the Geophysical Institute, University of Bergen, and funded by the Research Council of Norway under the project “Atmosphere-Ocean Interaction”, project no. 175763 (http://www.gfi.uib.no/~jenkins/SUP/) and the Norwegian Research School in Climate Dynamics (ResClim: http://www.resclim.no/).

There were approximately 40 participating scientists, from Norway, Europe, and North America, including approximately 10 Ph.D. students. A total of 17 scientific presentations were made (see Appendices A and B). Slides from the presentations may be obtained on application to the ResClim secretariat, e-mail address **post@resclim.no**

2. Discussion

During the course of the workshop a number of discussions were held. Salient points from these discussions are summarized below.

Remote sensing Ground truth experiments made in conjunction with new satellite design and launches tend to be rather fragmented. There is a requirement for dedicated field experiments, synergy amongst measurement of different parameters and use of different measurement techniques

Offshore wind power applications The recent encouragement of the development of offshore wind power generation provides new opportunities for dedicated instrument platforms, medium to long-term time series, opportunities for dedicated field campaigns. Other types of measurement may be made during such field campaigns, e.g. gas exchange – principal investigators in such topics are always looking for opportunities to perform fieldwork in conjunction with measurements of background parameters. It is also proposed to construct and instrument a number of masts/towers to obtain data from the atmospheric boundary layer, e.g. in Isfjorden (Spitsbergen). Model studies require a wide range of techniques covering different scales, from regional/global down to fine-scale CFD models, with a corresponding range of time scales. Applications of such models range from climatological data for design, down to minute-by-minute simulations to optimize grid loading and market conditions.

Flux of momentum, heat, and mass under conditions of very high wind speed is of great interest to investigators in the field of gas flux and related topics, such conditions being rather uncommon, and investigators are thus interested in participating in field campaigns where such conditions can be encountered.

Long time series of data sets with variable quality (e.g. voluntary ship observations) Careful statistical analysis should give results of good quality, attention should be given to the date sets' probability distribution functions (Weibull, modified Fisher-Tippett, etc.)

Long-term analysed ocean data sets such as NCEP and ERA40 are of great value and their quality needs to be evaluated carefully. In particular, the heat flux values from NCEP appear to be unreliable, and should be corrected using alternative parameters and data sets.

Establishment of an international program for air-sea interaction. This should focus on: what is the current state of the art, and significant gaps in our knowledge; how to integrate interdisciplinary competence to fill these gaps; and how to integrate remote sensing, in situ measurements, laboratory experiments, and numerical modelling.

Appendix A Program

Monday April 12

09:30 – 11:00 Registration

11:15 - 12:00 Guest lecture at Geophysical Institute, University of Bergen (UiB),
Laurence Padman, Earth & Space Research, Corvallis, Oregon
Roles of tides in polar oceanography, including melting of Antarctic ice shelves

12:30 – 13:30 Lunch

13:45 – 14:30 Welcome and introduction

14:30 - 14:50 Peter M. Haugan, Geophysical Institute, UiB
New opportunities for air-sea interaction research

15:00 - 15:30 Break

15:30 - 15:40 Marius Årthun, Geophysical Institute, UiB
Ocean heat loss and cold deep water formation in the Barents Sea

16:00 - 16:20 Ole Segtnan, Geophysical Institute, UiB [with Tore Furevik and Alastair D. Jenkins]
Heat and freshwater budgets of the Nordic Seas

16:30 - 16:50 Anna Sjöblom, The University Centre in Svalbard (UNIS)
Air-sea interaction in the High Arctic

17:00 End of afternoon session

Tuesday April 13

09:15 - 09:30	Introduction to day 2 of workshop
09:30 - 09:50	Craig McNeil, APL, University of Washington, Seattle *Variability in the ratio of N2 to O2 fluxes during storms and hurricanes*
10:00 - 10:20	Alastair D. Jenkins, UniResearch & Geophysical Institute UiB *An overview of the effects of ocean waves on the adjacent atmospheric and oceanic boundary layers*
10:30 - 11:00	Break
11:00 - 11:20	Hubert Branger, IRPHE/CNRS, Marseille *Air-flow characteristics in the very close vicinity of surface wind waves*
11:30 - 11:50	Johnny A. Johannessen, Nansen Environmental and Remote Sensing Center, Bergen *Satellite SAR range Doppler velocity retrievals*
12:00 - 12:20	Knut-Frode Dagestad, Nansen Environmental and Remote Sensing Center, Bergen *The need for acccurate, modelled ocean surface wave spectra for retrieval of wind, waves and currents from Synthetic Aperture Radar imagery*
12:30 - 13:30	Lunch
13:30 - 13:50	Andrei Pushkarev, Waves and Solitons LLC, USA and Lebedev Physical Institute, Moscow [with Donald Resio, and Vladimir E. Zakharov] *New understanding of wind input parameterizations*
14:00 - 14:20	Stanislav Ermakov, Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod *On damping of long waves due to interaction with short wind waves*
14:30 - 14:50	
15:00 - 15:30	Break
15:30 - 15:50	Sergei Gulev, IORAS, Moscow *Statistical determination of extreme turbulent air-sea heat fluxes*
16:00 - 16:20	Lars Robert Hole, met.no, Bergen BIOWAVE: *Surface wave effects in the upper ocean and consequences for biological modeling*
16:30	End of session, day 2
19:30	Workshop dinner

Wednesday April 14

09:15 - 09:30	Introduction to day 3 of workshop
09:30 - 09:50	Laurence Padman, Earth & Space Research, Corvallis, OR, USA *Tidal contribution to ocean/atmosphere heat and salt exchange through sea ice*
10:00 - 10:20	Øyvind Sætra, met.no, Oslo *Why ocean models need sea-state dependent momentum fluxes!*
10:30 - 11:00	Break
11:00 - 11:10	Siri Kalvig (StormGeo & University of Stavanger) and Olav Krogsæter (StormGeo & University of Bergen) *Introduction to discussion: Atmosphere-wave model coupling*
11:10 - 11:45	Discussion on atmosphere-wave-current-turbulence model coupling
11:45 - 11:55	Helene R. Langehaug, Nansen Environmental and Remote Sensing Center *Introduction to discussion: Open-ocean convection in numerical climate models*
11:55 - 12:30	Discussion on convection and regional/oceanic scale atmosphere-ocean interaction processes
12:30 - 13:30	Lunch
13:30 - 14:30	Final review/discussion and summary
14:30	End of workshop

Appendix B Abstracts

New opportunities for air-sea interaction research

Peter M. Haugan

Geophysical Institute, University of Bergen

The recent surge in activity concerning offshore wind energy has led to a renewed interest in the marine atmospheric boundary layer and ocean near surface conditions. Offshore wind turbines tend to be larger than onshore and therefore more prone to damage if not controlled in near real time based on observations and models. The floating structures are exposed to waves and currents over a considerable depth. New instrumentation for measurements and understanding of the forces and their interaction with structures is now becoming available. While applied research with immediate wind energy applications must have priority, the data collected, the infrastructure itself and the models developed can also give new opportunities for basic research. I will ask if the air-sea interaction research community is ready to exploit these opportunities.

Another opportunity stems from the increasing realisation in climate research of the importance of ocean surface conditions on the state of the atmosphere including cloudiness (albedo) and moisture transport and precipitation (over land). Areas with upwelling and strong and variable ocean fronts such as around the southern tip of Africa within the Agulhas and Benguela systems provide natural laboratories for air-sea interaction process studies. The existing knowledge and capability in South Africa and a new research centre being set up in Cape Town in 2010 with Norwegian partnership opens possibilities for new field work in the region as well as for ocean-atmosphere model studies and data analyses exploiting remote sensing and in situ observations.

Ocean heat loss and cold deep water formation in the Barents Sea

Marius Årthun
Geophysical Institute, University of Bergen

Dense water masses form on the Arctic and Antarctic shelves through cooling and rejection of salt during sea-ice growth. Deep and bottom water in the world can partly be explained by subsequent shelf convection. Large-scale lateral advection from the adjoining continental shelves also maintains the cold upper halocline of the Arctic Ocean. Hence, the brine enriched water's cascading off the continental shelves is crucial for the global ocean circulation and climate.

The Barents Sea is of particular interest. According to estimates based on atmospheric observations and oceanic heat budgets, about half of the heat loss in the entire Nordic Seas takes place here (Simonsen and Haugan 1996). It is also one of the largest shallow shelves adjacent to the Arctic Ocean, and the deepest (230m). The ice extent shows large seasonal variations (Kvingedal 2005), which provides favourable conditions for ice formation and subsequent brine release. Cold Deep Water (CDW, T<0°C, S>34.75 psu) is observed to form on the shelves near Novaya Zemlya and Storfjorden, and also in shallow areas as the Central Bank (Midttun 1985).

The current project aims to increase the understanding of the variability in hydrography and biogeochemistry which preconditions the surface ocean prior to ice formation. Mesoscale processes in the Barents Sea related to sea ice, deep water formation and air-sea exchange, and their interannual and decadal variability, will be studied using the high resolution regional coupled ice-ocean model HAMSOM.

Heat and freshwater budgets of the Nordic Seas

Ole Henrik Segtnan

Geophysical Institute, University of Bergen

The heat and freshwater budgets of the Nordic Seas are studied. Apply- ing the available data sources the different terms of the heat and freshwater budgets are calculated. Integrated over the Nordic Seas area, the residu- als of the annual mean heat and freshwater budgets are 3 TW and 4.4 mSv (1 Sv = 10^6 m^3 s^{-1}). Budgets are also computed for five subregions within the Nordic Seas. Here the residuals are ranging from −21 TW to 28 TW and from −25.6 mSv to 46.6 mSv. This is assumed to be related to insufficient information of the horizontal heat and freshwater fluxes, in particular the eddy transports that are not included in the calculations. In order to close the budgets the residuals are interpreted as real ocean eddy heat and fresh- water fluxes. Then the transfer rates across the Arctic Front that separates the Greenland and Iceland Sea from the Norwegian Sea become −25 TW and 25 mSv. The greatest ocean heat loss occurs in the Norwegian Sea, with a net heat loss close to 100 TW. Here also the greatest freshwater input is found, with a net transport of approximately 40 mSv.

Air-sea interaction in the High Arctic

Anna Sjöblom

University Center in Svalbard

The Atmospheric Boundary Layer over water in the High Arctic has been studied using long-term measurements from a fjord in the archipelago Svalbard with complimentary measurements from short term campaigns over the Arctic Ocean. Here, the different field experiments will be presented. It will be shown how the air-sea interaction in a fjord is different from the air-sea interaction in the open ocean. This is mainly due to topographic effects but the shape of the fjord also plays a significant role. In addition it has been shown by modelling studies that the spatial variability is large. Therefore, momentum and sensible heat fluxes are modified from those found over open ocean and the commonly used Monin-Obukhov similarity theory can not always be used in fjord systems.

Variability in the ratio of N_2 to O_2 fluxes during storms and hurricanes

Craig McNeil
Applied Physics Lab, University of Washington

Air-sea fluxes of N_2 and O_2 have been measured during winter storms in the NE Pacific, a summer storm in the NE Atlantic, Hurricane Frances in the NW Atlantic, and Hurricane Gustav in the Gulf of Mexico. Time series data collected on a mooring was used in the NE Pacific study, while data collected from profiling floats was used in the other studies. Dissolved N_2 was measured by the gas tension method. Gas fluxes during the wind events were estimated using one-dimensional mixed layer budgets. Waterside O_2 covariance fluxes were also measured on the floats by ballasting them to be nearly neutral and estimating O_2 fluxes from the measured O_2 time series during the Lagrangian drift of the floats in the ocean boundary layer. The N_2/O_2 flux ratio provides information on the bubble mediated processes that control the net air-sea fluxes of these gases. Results of a preliminary study that investigated the variability in the gas flux ratio during individual storm events and inter-comparisons of flux ratios during different storm events will be presented.

An overview of the effects of ocean waves on the adjacent atmospheric and oceanic boundary layers

Alastair D. Jenkins
UniResearch and Geophysical Institute, University of Bergen

Ocean waves are an integral part of the coupled atmosphere-ocean system, being supported by the gravitational restoring force on the air-water density jump, and forced from the atmosphere-ocean velocity difference mediated by boundary-layer turbulence and hydrodynamic instability mechanisms. To model their effects it is advantageous to employ surface-following coordinate representations in order to resolve rapid vertical variations of dynamical and physical variables near the sea surface. It is also necessary to pay particular attention to coordinate representations in the study of the interaction of the mean flow with the wave motions (for example when estimating wave-induced current) and when interpreting the results of measurements from observing platforms which have wave-induced motions. Steep, breaking waves disrupt the water surface topology and influence strongly the atmosphere-ocean transport of mechanical energy, heat, and mass (including gas species). An overview of the foregoing phenomena will be presented, with reference to the current state of the art, applications, and future prospects.

Air-flow characteristics in the very close vicinity of surface wind waves

Hubert Branger

Institut de Recherche sur les Phénomènes Hors Équilibre, Centre National de la Recherche Scientifique

During the mechanical energy transfer from wind to water waves, one part of the energy contributes to amplifying the waves through the form-drag, whilst the other part contributes to the drift current through the viscous stress. Depending on the air and waves conditions, the repartition form drag / viscous drag is not yet well known. In the large IRPHE air-sea interaction facility in Marseilles we have developed a new experimental system to measure wind characteristics very close to the water surface, even in the viscous sub layer. An original device “diver” facilitates the passing of an air-speed probe through the viscous sub-layer which allows the shear stress at the surface to be determined. We developed also a static pressure probe to measure the pressure fluctuations above waves. This probe was put on a wave-follower system to measure pressure fluctuations, above crest but also in the troughs of the waves. These measurements provide a thorough description of the local structure of the wind in all the zones that are very close to the water surface. We are therefore able to show that the viscous stress contribution to the total stress is a decreasing function of the wind and of the dominant wave slope. We are also able to show that the viscous stress is not constant along the wave’s profile but that it presents modulations which are a function of the wave’s phase and which increase with the wave slope. Pressure wave induced perturbations are also presented.

The need for acccurate, modelled ocean surface wave spectra for retrieval of wind,waves and currents from Synthetic Aperture Radar imagery

Knut Frode Dagestad

Nansen Environmental and Remote Sensing Center

Synthetic Aperture Radars (SAR) provide high resolution (~10-100 m) measurements of the ocean surface roughness on centimeter scale. Empirical models which relate this roughness to surface wind are used to calculate the wind speed with an accuracy of 1-2 m/s. Recently it has become clear that also the Doppler shift (Doppler Centroid Anomaly) from the SAR measurements contains useful geophysical information related to winds and currents. This Doppler shift is available at coarser scale (~5 km), and is due to orbital motion of waves, velocity of breaking wave fronts, and the surface current. An empirical relationship between this Doppler shift and the wind has also been derived, through the clear relation between wind and wave orbital velocity, neglecting at first order impact from ocean surface current. Subsequently, for situations with strong currents, the wind contribution can then be subtracted, and the Doppler velocity due to currents remain as an anomaly. A good agreement with in situ observations from the Agulhas current system has been found, whereas a fair qualitative relationship has been found for the Norwegian Coastal Current, which is weaker and often masked by variable wind. Several examples will be shown to illustrate the capability of SAR to image mesoscale wind and current systems.

To advance further, a combined and consistent retrieval of wind, waves and currents should be performed by combining both the roughness (kinematic) and Doppler (dynamic) measurements. This is not feasible with empirical models, and instead physical "forward" models should be used to calculate these observable quantities from first guess wind-wave-current fields, and then compare with the measured values. The wind-wave-current fields may then be modified iteratively until a best match with the SAR measurements is obtained. The central problem in this approach is to determine an ocean wave spectrum very accurately at scales of centimeters to meters, as both the roughness and Doppler shift can be calculated from this spectrum with electromagnetic scattering theory. The main challenge lies in describing how the wave spectrum changes over short scales due to wave-current, wave-wave, and ocean-atmosphere interaction. This appoach and the physical models used will be decribed in more detail.

New understanding of wind input parameterizations

Andrei Pushkarev

Waves and Solitons LLC and Lebedev Physical Institute, Russian Academy of Sciences

It is well known that wind waves parameters observed in dozens of different experiments can be approximated by unique regression line. We present new vision of wind input term, associated with intrinsic structure of Hasselmann equation, which reproduces this regression line. Theoretical analysis is compared with numerical simulation.

On damping of long waves due to interaction with short wind waves

Stanislav Ermakov

Institute of Applied Physics, Russian Academy of Sciences

Interaction between long and short gravity wind waves is investigated on the base of coupled equations for the long wave amplitude and the spectrum of short wind waves. It is shown that the equation for long waves contains an additional term proportional to a gradient of the short wave spectrum. Variations of the short wave energy are described by the kinetic equation for the spectrum of short waves in the presence of the long wave orbital velocity currents. Relaxation of short wind waves results in damping of long waves, and an expression for the damping coefficient of long waves is obtained. The damping of long waves is analysed for the cases of short wind waves on clean water surface and in the presence of elastic organic films. It is shown that strong depression of centimeter-scale wind ripples in organic slicks leads to reduction of the damping coefficient of decimeter-scale waves, and, therefore, to larger intensities of these waves compared to the case of clean water surface. The effect of amplification of the spectrum intensity of decimeter-scale waves in slicks is estimated using a simple model of local energy balance of wind waves, and the obtained spectrum contrasts are shown to be in reasonable agreement with experimental results. Preliminary estimation of the damping of swell due to interaction with wind waves is also made, and the swell damping coefficient is obtained to be very small. The work has been supported by RFBR (Project 08-05-00634-a) and IPY THORPEX.

Statistical determination of extreme turbulent air-sea heat fluxes

Sergei Gulev

Sea-Air Interaction and Climate Laboratory, Russian Academy of Sciences

We developed a new probability density distribution for surface turbulent fluxes of heat and moisture over the global ocean. This distribution is called the modified Fisher-Tippett (MFT) distribution and is based on the family of the Fisher-Tippett distributions. Application of this distribution allows for accurate estimation of surface flux statistics and quantifying extreme fluxes at sea surface. We present accurate estimates of different surface turbulent flux statistics derived from reanlayses (NCEP and ERA-40) as well as from the VOS-based fluxes. Our approach allows also for the estimation of extreme fluxes quantified through the high percentiles (99th, 99.9th, 99.99th) of turbulent fluxes. These estimates cannot be accurately derived form the raw data and require analysis of the theoretical PDFs. Extreme turbulent fluxes estimated from the MFT distribution may amount to 2000-3000 W/m2 for the latent heat flux and up to 2000 W/m2 for the sensible flux. For the VOS fluxes MFT distribution allows for the minimization of sampling errors in climatologically averaged estimate through the application of the theory of the censored samples to MFT distribution. This procedure reduces sampling errors in subpolar and high latitudes by 2-8 times and provides more accurate estimates of VOS-based surface fluxes. Analysis of climate variability of extreme surface fluxes allowed for identification of trend patterns and interannual variability modes which are different from those in the mean flu values. This implies long-term changes in the character of probability distributions of fluxes. Some examples of variability of surface turbulent fluxes based on VOS for the period from 1880 to 2008 are presented.

BIOWAVE: Surface wave effects in the upper ocean and consequences for biological modeling

Lars Robert Hole
Norwegian Meteorological Institute

The Norwegian Meteorological Institute (met.no) and the Institute for Marine Research (IMR) have a national responsibility for providing information on weather, ocean currents and sea state for planning and protection of the environment, and to give advice to Norwegian authorities on aquaculture and the ecosystems of the Norwegian waters. Ecosystem models are used by met.no and IMR to model, explore and monitor phytoplankton dynamics, zooplankton, fish eggs and larval growth, transport and spreading. These models are our key tools to study productivity in the ecosystems and, particularly, recruitment to the fish stocks. Moreover, such models are necessary tools for assessing the vulnerability of marine plankton, hereunder fish eggs and larvae, to floating and dispersed pollutants. Our main objective is to improve the operational system for forecasting and monitoring of fish egg and larvae transport. The purpose of BioWave is to study the mixed-layer dynamics of the numerical circulation models as applied for the physical forcing in ecosystem models. We will include wave-induced fluxes of momentum and energy, which gives a more realistic description of the ocean currents and turbulent mixing in the upper layer of the ocean. The wave-induced fluxes will be implemented in the ocean circulation model using the theoretical framework of Broström et al. (J. Phys. Oceangr., 2008). The operational wave prediction model at met.no will produce the necessary forcing fields for the ocean circulation model, and hence the wave model will act as a link between the atmosphere and ocean models. The ocean circulation model will subsequently deliver improved physical forcing fields for the operational ecosystem models used by IMR. An extensive field campaign for the purpose of model verification is planned for the waters off Lofoten and Vesterålen. This is the core region for cod spawning in Norway.

Satellite SAR range Doppler velocity retrievals

Johnny A. Johannessen
Nansen Environmental and Remote Sensing Center, Bergen

Regular access to Doppler shift measurements from Envisat Advanced Synthetic Aperture Radar (ASAR) Wide Swath Mode (WSM) images is now possible. An increasing data set of the radar-detected ocean surface roughness velocities inverted from the Doppler shifts has therefore emerged dating back to mid 2007. This offers an innovative capability to establish time series and gridded maps of Doppler-derived ocean surface velocities. Building on more than 1000 acquisitions from the greater Agulhas Current, the robust results give confidence that the Envisat ASAR can be used as a speed-gun from space. Combined with surface drifter data and altimeter measurements, these new products strengthen the routine monitoring of the intense current regimes.

Tidal contribution to ocean/atmosphere heat and salt exchange through sea ice

Laurie Padman

Earth and Space Research

The presence of sea ice has a profound effect on the rate of heat exchange between the ocean and atmosphere. Sea ice responds to stress applied by the underlying ocean currents. Spatial variability in this stress (shear and strain) influences mean ice roughness characteristics and the mean fraction of open water (leads) in the ice pack. In many regions of the Arctic and Antarctic seas, notably along coastlines and over the continental slope, tides are the dominant source of ocean kinetic energy. Periodic divergence of the ice pack due to tides increase time-averaged open water fraction, enhancing ocean/atmosphere heat exchange and subsequent freshwater fluxes associated with ice formation and melt. This presentation describes the contribution of barotropic and baroclinic tides to sea ice evolution and ocean/atmosphere fluxes using both data (SSM/I) and numerical coupled ocean/sea-ice models.

Why ocean models need sea-state dependent momentum fluxes!

Øyvind Sætra

Norwegian Meteorological Institute

It is a well-known fact that surface waves carry mean momentum. Numerical general ocean circulation models are widely used to predict oceanic motions caused by the wind. Such models are usually based on an Eulerian description of motion. Furthermore, they often assume hydrostatic balance in the vertical, and accordingly they do not capture wind-induced surface waves. When the wind is blowing over the ocean, a large fraction of the total momentum flux goes into wave momentum as Stokes drift. When waves dissipate, mostly through wave breaking, wave momentum is released to ocean mean currents. In this way, the wave field can redistribute the momentum extracted from the atmosphere in time and space. We argue that for a realistic description of the air-sea transfer of momentum, ocean models needs to be forced by stresses calculated from an ocean wave model. The impact of this has been studied using surface stresses calculated from a numerical wave model to force a storm surge model over a one year period. In addition a control simulation, using standard parametrization for the stress calculations, was performed over the same period. The results were validated against 22 sea-level stations in the North Sea.