

STATEMENT OF GUIDANCE FOR SUB-SEASONAL TO LONGER TIME SCALE PREDICTIONS

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1. Introduction

This State of the Guidance (SoG) outlines observational data requirements for the sub-seasonal to longer predictions. In this revision, the scope of the SoG was expanded to reflect emerging user requirements of operational services to provide predictions at sub-seasonal to decadal timescales (herein roughly two weeks to 10 years). The sub-seasonal and seasonal predictions are often made using dynamical models either atmospheric general circulation models (AGCMs) or coupled general circulation models (CGCMs). A sea ice component is also coupled in some CGCMs. Therefore, this SoG focuses on the requirements to exploit the predictions with the dynamical models.

The physical basis for seasonal and inter-annual prediction lies in components of climate that vary slowly compared with individual weather events, i.e. ocean and land (including cryospheric components). Among them, the ENSO (El Niño Southern Oscillation) cycle is, for instance, the most relevant phenomenon with predictability on the seasonal time-scale. ENSO consists of a coherent large-scale fluctuation of ocean temperatures, rainfall, and atmospheric circulation across the tropical Pacific, but has a vast influence on global climate conditions. It is a coupled ocean–atmosphere phenomenon, and can be relatively well predicted a few seasons ahead. This predictability, together with its widespread influence on climate variability, makes ENSO the dominant source of predictive skill for any seasonal to inter-annual forecast systems. Other coupled ocean–atmosphere phenomena are also recognized and predictable to some extents (e.g. Indian Ocean Dipole). Ocean observations are essential to initialize CGCMs in order to predict these phenomena. Other observations are also essential. For instance, land surface conditions play a role during the first two months of the forecast. Sea ice becomes increasingly important for the seasonal prediction. It is also noted that some modelling groups now include the stratosphere in their seasonal forecast systems. On time scales beyond one or two months, the models would also need to include up-to-date long-term forcing (e.g. greenhouse gases, volcanic aerosol, solar irradiance).

In order to predict seasonal climate by dynamical means, fully coupled ocean–land–atmosphere models are generally used. Just as in weather prediction, ensemble forecasts using these coupled models give probabilistic risk forecasts of climate events. To initialize the coupled model, observations of the atmosphere, land and ocean are used. There is large variation in the approach to initialize the ocean component (e.g. Martin et al. 2015), with some of the simpler schemes using only wind information while the more complex models usually assimilate sub-surface temperature and salinity data, and satellite surface topography and temperature data. Indeed, major challenges remain in the development of assimilation techniques that optimize the use of observations in initializing coupled models. For example, coupled data assimilation techniques are a major area of current research. It is noted that historical data sets also play an important role in sub-seasonal and longer predictions by supporting calibration and verification activities, since the error characteristics are flow-dependent and long-term consistent observations are needed for their correction.

In recent years the capabilities in sub-seasonal predictions have developed substantially. By sub-seasonal predictions we mean predictions beyond 10 days but not extending to a full season. In 2013 a joint WWRP/WCRP project on sub-seasonal to seasonal prediction started. The main goal of this research project is to improve forecast skill and understanding on the sub-seasonal to seasonal timescale, and promote its uptake by operational centres and exploitation by the applications community. Forecasting in the intermediate range between medium and seasonal range is difficult as the importance of atmospheric initial conditions wanes and the effect of slower boundary conditions of the atmosphere such as sea surface temperature increases. Coupled

ocean-atmosphere modes that modulate variability on subseasonal and seasonal timescales (respectively e.g. MJO and ENSO) require CGCMs for comprehensive prediction and these are the preferred tool, although for windows when persistence of SST anomalies is reasonable uncoupled systems can be used. The observational data requirements for sub-seasonal forecasts are the same as the ones for seasonal and inter-annual forecasts, with emphasis on higher spatial and time resolutions to facilitate better initialization of models with higher resolution compared with those used for the seasonal prediction.

Efforts have been made to the multi-annual to decadal prediction in the research, and informal exchange of real-time multi-annual prediction data has been continued in the last few years. Currently one operational centre and several research groups contribute to this exchange. The decadal prediction needs observations of the ocean, favourably including the deep ocean, to be initialized, and climate forcing (e.g. greenhouse gases, volcanic aerosol, solar irradiance) to be specified. In addition, some observation and reconstruction data are required to address the key decadal variability (e.g. Atlantic Meridional Overturning Circulation (AMOC), Atlantic Multidecadal Variability (AMV), Pacific Decadal Oscillation (PDO)).

In this SoG, the observational requirements and the gap analysis of sub-seasonal to longer forecasts are based on a consensus of the coupled ocean–atmosphere modelling community. The gap analysis between user requirements and current observing system capability is given in the following sections. Since the scope of the SoG is relatively wide, and requirements are essentially the same for the Global NWP or Ocean Applications in some relevant parts, here we focus on elements, which are particularly important for initialization, validation and calibration of the sub-seasonal to longer time scale predictions, and development of their systems. With regards to requirements for initialising the atmosphere and land, please refer to the SoG of Global NWP. It is also noted that there is on-going research and development to integrate medium-range and seasonal prediction systems into coupled models/assimilation systems.

2. Gap Analysis: User Requirements and Observing System Capability

2.1 Ocean and Ocean-related variables

As mentioned above, success in the sub-seasonal to longer time scale forecasting derives, to large degree, from predictable fluctuations in the (mainly tropical) ocean and ocean observations are therefore of key importance. The ocean observing system has been implemented based on the international coordination under the Intergovernmental Oceanographic Commission (IOC, UNESCO), WMO and the Global Ocean Observing System (GOOS, WMO/UNEP/ICSU). In response to the Framework for Ocean Observing (FOO) the “Essential Ocean Variables¹” (EOVs) were identified (Lindstrom et al. 2012). The regional panels for the ocean observation were developed, for instance, TPOS2020 for the tropical Pacific, AtlantOS for the Atlantic Ocean, IndOOS for Indian Ocean (see the CLIVAR Exchanges Special Issue No. 67). There are other activities for evaluation of ocean observations in the CLIVAR Global Synthesis and Observations Panel (GSOP)², GODAE Ocean View (GOV) Observing System Evaluation Task Team (OSEval-TT)³. The current status of the real-time in situ Global Ocean Observing System was reviewed by Legler et al. (2015), and the satellite observation part was reviewed by Le Traon et al. (2015). Oceanic observation requirements relevant to the subseasonal to longer time scale predictions were also discussed in some reports of these activities (e.g. Fujii et al. 2015; Balmaseda et al. 2014).

2.1.1 Sea-surface temperature

¹ <http://ioc-goos-oopc.org/obs/ecv.php>

² <http://www.clivar.org/panels-and-working-groups/gsop/gsop.php>

³ <https://www.godae-oceanview.org/science/task-teams/observing-system-evaluation-tt-oseval-tt/>

Accurate Sea Surface Temperature (SST) determination is important for sub-seasonal to seasonal prediction models. Ships and moored and drifting buoys provide in situ observations with *acceptable* accuracy, but coverage and frequency are *poor or marginal* over large areas of the Earth. Instruments on polar satellites provide information with global coverage in principle, *good* horizontal and temporal resolution and *acceptable* accuracy (once they are bias-corrected using in situ data), except in persistently cloud-covered areas (which cover significant areas in the tropics). Geostationary imagers with split window measurements help to expand the temporal coverage by making measurements hourly and thus creating more opportunities for finding cloud-free areas and characterising any diurnal variations (known to be up to 4 degrees Celsius in cloud free regions with relatively calm seas). Microwave measurements provide *acceptable* resolution and accuracy and have the added value of being able to retrieve SST in cloud-covered areas. Blended products from the different satellites and in situ data are *good* in terms of temporal frequency, accuracy and coverage for sub-seasonal to seasonal forecasts. Observation of the diurnal cycle is becoming increasingly important, for which present and planned geostationary satellites offer a capability. High quality, fast delivery SST products are very important for the progress of sub-seasonal to seasonal predictions. Currently the accuracy and spatial scale of such diurnal SST products are only *marginally adequate*.

2.1.2 Ocean wind stress

Ocean wind stress is a key variable for driving ocean models. Current ocean data assimilation systems used for the initialization of the ocean employ winds derived from Numerical Weather Prediction (NWP) or, in some cases, winds inferred from atmospheric models specified with current SST fields. The tropical moored buoy network has been a key contributor for surface winds over the last decade, particularly for monitoring and verification, providing both *good* coverage and accuracy in the equatorial Pacific for calibration and validation of satellite data and assimilation products. Fixed and drifting buoys and ships outside the tropical Pacific provide observations of *marginal* coverage and frequency; *acceptable* accuracy for the same purpose. Although the coverage and frequency of in situ oceanic surface wind data are *not sufficient (or poor)* for atmospheric data assimilation systems, assimilating those data has a pronounced impact on the analysed wind speed, contributing to better oceanic initial conditions. The data have good accuracy and frequency, and *acceptable* coverage for purposes of ocean data assimilation.

Satellite-derived surface-wind speed and direction assessments by scatterometers are now the dominant source of this information, complemented with wind speed measurement by passive microwave imagers. Currently ocean initialization for the sub-seasonal to seasonal prediction is benefited mostly through the assimilated surface wind products of NWP, where their positive impact is acknowledged. Overall, the scatterometers provide *good* coverage and *acceptable* frequency and accuracy, and it complements the ocean-based observations. High-quality scatterometer winds are the best products available at the moment and need to be maintained operationally.

2.1.3 Sub-surface temperature

Most of operational ocean/coupled assimilation systems for the sub-seasonal to seasonal prediction take advantage of sub-surface temperature and salinity observations, at least in the upper ocean (down to ~500 m depth). The Tropical Atmosphere Ocean (TAO)/Triangle Trans-Ocean Buoy Network (TRITON) moored buoy network provides data of *good* frequency and accuracy, and *acceptable* spatial resolution, of sub-surface temperature for the tropical Pacific, at least for the current modelling capability. Although the TAO/TRITON network has been a backbone of observational monitoring in the tropical Pacific, data return decreased from 80-90 % to below 30 % in 2013–2014 due to logistic and funding problems. This situation was recovered by provisional logistics this time. On the other hand, the TRITON array has also gradually been decommissioned due to lack of research funding and changes in the supporting agency. These situations urged the operational and research communities to coordinate and redesign a

sustainable and cost-efficient observation system (TPOS2020). The tropical moored buoy network in the Atlantic, Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) has *better than marginal* spatial resolution. The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) array provides coverage over the Indian Ocean.

The sub-surface measurement of the Expandable Bathy Thermographs (XBTs), coordinated by Ships-Of-Opportunity Programme (SOOP), provides data of *acceptable* spatial resolution over some regions of the globe, but the temporal resolution is *marginal*. It is noted that SOOP is evolving to provide enhanced temporal resolution along some specific lines.

Free-drifting profiling floats deployed under the Argo project (Riser et al. 2016) provide global coverage of temperature and salinity profiles to ~2000 m depth, mostly with *good* spatial resolution globally, *and acceptable* frequency, except for the regions around the equator, western boundary current regions and marginal seas. Around the equator, their coverage is marginal due to the surface divergent current. It is also noted that the general types of Argo floats are also unable to sample in ice-covered and shallow areas (e.g. the Maritime Continent), but new research floats are successfully deployed in Antarctic sea ice areas (Wong and Riser 2011). In all cases the accuracy is *acceptable* for sub-seasonal to seasonal prediction purposes. The Argo floats derive substantial benefit for the global ocean analysis for sub-seasonal to seasonal forecasts, thus the Argo are currently indispensable component of the global ocean observing system. Moorings at and near the equator are important to complement the ARGO float measurement in this area.

2.1.4 Salinity

Salinity is an important parameter, and is becoming increasingly used in assimilation for sub-seasonal to decadal prediction systems. Many ocean data assimilation systems make use of the temperature and salinity profiles instead of temperature profiles only (e.g. Fujii and Kamachi 2003, Ricci et al. 2005, Troccoli et al. 2002). The Argo is a major source of salinity observations. It provides *good* global coverage of temperature and salinity profiles to ~2000 m, mostly with *acceptable-to-good* spatial resolution, and *acceptable* temporal resolution in the tropics. Valuable data also comes from some of the tropical moorings, in particular from the TRITON buoys, although data coverage is rather limited. Surface salinity is also measured by satellite such as Aquarius and SMOS with *good* coverage, *acceptable-to-good* spatial resolution and *poor-to-marginal* accuracy and frequency. Despite the limitation of accuracy, the satellite sea surface salinity has potential in the ocean assimilation (e.g. Toyoda et al. 2015), and there will be a need for continuity of these measurements. Constraining salinity in the ocean data assimilation is still a challenge, since there is large uncertainty in the fresh water flux (precipitation, evaporation and river runoff), affecting the surface salinity and mixed layer properties.

2.1.5 Ocean topography

Ocean altimetry provides measurements of the sea surface topography relative to the geoid (or mean sea-surface position) that in turn is a reflection of thermodynamic changes over the full-depth ocean column. In principle, the combination of altimetry, tropical mooring and Argo provides a useful observing system for initialising the thermodynamic state in sub-seasonal to seasonal prediction models. Altimetry from Jason-2, CryoSat-2 and AltiKa are currently used in operational ocean assimilation systems. Long-term commitments for satellite altimetry observation are required. It is noted that recently Jason-3 was successfully launched in January 2016, and expected to continue measurement of altimetry. Research satellites are providing a mix of data with *acceptable* accuracy, spatial resolution and frequency. Provision of global coverage beyond the tropical Pacific is an important requisite, in particular, for higher resolution coupled models (ocean resolution of ~30 km), in which there is partial representation of ocean eddies. In situ sea level measurements are useful particularly for testing models and validating altimetry.

2.1.6 Surface heat, radiative and freshwater fluxes

There are a few sites in the tropical ocean where the data on surface heat flux are of value for validation and are required at a number of sites in the tropical oceans. NWP products (derived from predictions in the assimilation window), in principle, have *good* resolution and frequency, but the accuracy is at best *marginal*. Satellite data provide prospects for several of the components of heat and radiative fluxes, particularly shortwave radiation, but at present, none is used on a routine basis in assimilation for sub-seasonal to seasonal predictions, due to some technical difficulty in use over sea ice areas. Precipitation estimates are important for validation because of the fundamental role of the hydrological cycle in sub-seasonal to seasonal prediction impacts. They also have importance in initialisation because of the links to salinity. However, there remain significant uncertainties in estimates of rainfall over the oceans. In addition the fresh water run-off information from rivers (large estuaries) will become important in coastal areas and regional parts of the oceans (e.g. the Bay of Bengal). Additional data would always be useful, for example, data to allow better estimation of heat fluxes and P–E (precipitation minus evaporation) could help give a better definition of the mixed layer structure.

2.1.7 Ocean current data

Most ocean data assimilation systems do not use ocean current data but some systems update ocean current fields using either dynamical or statistical relationships. Because of the central importance of dynamics and advection, the ocean current data are important for testing and validation. The ocean current is measured and analysed by in situ or remotely-sensed observations. For example, surface currents measured by drifting buoys are *acceptable* in terms of accuracy and temporal resolution but *marginal* in spatial coverage. Moored buoy observation has *good* in accuracy and frequency but *poor-to-marginal* in spatial coverage. Satellite altimetry is also being used to infer the distribution of near-surface ocean currents. The Ocean Surface Current Analyses (OSCAR) for the tropical Pacific and Atlantic are now being produced routinely by blending geostrophic estimates from altimetry with Ekman estimates from remotely-sensed wind observations.

2.1.8 Sea ice

Sea-ice cover is important not only for high latitudes, but for mid-latitudes. It is provided together with many SST products. Sea-ice concentration products like the EUMETSAT OSI SAF, derived from SSMIS brightness temperatures, are valuable. Daily global observations are provided routinely since 1979. However uncertainties are large in presence of melt ponds and young ice. The sea-ice cover data have *acceptable* accuracy and temporal resolution and *good* coverage.

Sea-ice thickness is also required to better determine the sea-ice initial state and the conductive heat fluxes through the ice. In situ sea-ice thickness is rather limitedly available. Sea-ice thickness assessments produced with satellite observations like ICESat (Ice, Cloud and land Elevation Satellite) have high spatial resolution but narrow swath width. CryoSat and CryoSat-2, through use of a satellite in low Earth orbit, monitor variations in the extent and thickness of polar ice. SMOS sea-ice thickness data are restricted to detect thin sea ice (< 1 m) and has complex error characteristics. These satellite-based sea-ice thickness products are overall poor to *marginal* accuracy. Although they have *acceptable* temporal resolution and spatial coverage currently (after CryoSat). How to assimilate the thickness data effectively is still an on-going area of research. The sea-ice observations may have potential benefit for the multi-annual prediction in the future, although to date the impact has not been fully evaluated.

2.1.9 Deep sea

The observation of the deep sea has relied on ship-based measurements for several decades, but it was rather limitedly available due to the cost. In recent years, the deep Argo program has been developing the free-drifting profiling floats that are capable of observing the deep ocean below 2000 m to 4000 m or 6000 m depending on the float types. The deep Argo floats cost more than the regular Argo floats, but much less than the ship-based measurements. More than 50 deep temperature/salinity sensors are also deployed by the OceanSITES project (<http://www.oceansites.org/index.html>), and the project plans to increase the number of the sensors further. Although it is still difficult to assess impacts of those new platforms, deep sea observations may be beneficial for decadal prediction and climate projection, at least for purposes of validating predictions. Monitoring of the Atlantic Meridional Overturning Circulation (AMOC) with the RAPID array along 26°N is also important for validating decadal predictions.

2.2 Land variables

Requirements of the land observation for sub-seasonal to seasonal predictions coincide with those of the Global NWP application. It is noteworthy that sub-seasonal to seasonal prediction requires long-term data with consistent quality over periods that include the model reforecast period (typically the past 20 years or longer) to facilitate optimum calibration of the predictions.

2.2.1 Snow

Snow depth and snow cover have major effects on surface albedo and energy balance, and modify surface temperature and overlying atmospheric conditions. Snow cover is remotely measured by visible and near infra-red satellite imagery. The information has *good* horizontal and temporal resolution and accuracy but it is provided only during daytime and in cloud-free areas. Snow depth observations are *insufficient (poor)* for the purpose of initialising sub-seasonal to seasonal predictions. Although surface SYNOP stations report measurements of local snow depth with high accuracy, the coverage of SYNOP stations reporting snow depth is *not adequate (poor)* (see also SoG for the Global NWP). Microwave imagery has also the potential for improvement of snow mass assessment in the land analysis.

2.2.2 Soil moisture

Soil moisture is a crucial element in the sub-seasonal and seasonal forecast performance in mid-latitudes in boreal spring/summer. Due to its extended memory, the relevant quantity to initialise is the soil water in the root layer (a soil layer with a depth of about 1 m). Low-frequency microwave imagery and scatterometer measurements are sensitive to surface wetness with an insufficient penetration depth (i.e. they do not penetrate the full root layer). At present only the Soil Climate Analysis Network (SCAN) provides a network of real-time vertical profiles of soil moisture and coverage is limited to the whole United States' area. A network of similar measurements covering the global domain would be very useful. The current operational soil moisture product from ASCAT has *acceptable* spatial resolution but *marginal* accuracy. Passive L-band microwave imagers such as SMOS and SMAP have great potential.

2.2.3 Other land variables

As for the Global NWP application, vegetation type and cover is provided by operational satellite imagery and near infrared channels. The accuracy of such products is generally *marginal*. However MODIS has a considerably improved accuracy.

2.3 Climate forcing variables

2.3.1 Aerosol and greenhouse gases

As for the NWP models, aerosols data (including volcanic aerosols) and stratospheric ozone concentration data have been recently used in several sub-seasonal to decadal prediction systems. Especially stratospheric sulfate aerosols injected by large explosive volcanic eruptions such as that of Mount Pinatubo in 1991 had significant impacts on global climate, and its influence can last a few years. Sub-seasonal to decadal predictions require geographical distributions of aerosol loading with 1–2 km in the vertical and monthly time resolutions.

Satellite instruments such as high resolution infrared sounders and solar backscatters provide accurate measurements of total column ozone. However, vertically resolved ozone information is needed. Microwave limb sounders have the potential to offer good vertical resolution and accuracy.

2.3.2 Solar irradiance

Observed solar irradiance is utilized in some seasonal to decadal prediction systems, and its use has been shown some impacts on the predictions at these time scales (e.g. Ineson et al. 2011). Spectral irradiance is measured by Spectral Irradiance Monitor (SIM) and SOLar STellar Irradiance Comparison Experiment (SOLSTICE) instruments aboard the Solar Radiation and Climate Experiment (SORCE) satellite mission. Although data are currently available for the limited period (2004–present), and it would be hard to evaluate the accuracy, continuous observation of the spectral irradiance is required for the seasonal to decadal predictions. Some studies suggested that UV (200–400 nm) irradiance analysis with monthly time resolution are required for seasonal to decadal predictions.

2.4 Atmospheric data

Similar to the NWP models, the atmospheric components of most sub-seasonal to seasonal prediction systems are initialized by an accurate analysis of the state of the atmosphere and earth's surface. Therefore the observational requirements are similar to those for the Global NWP application (see SoG for Global NWP). However, the longer integrations relative to NWP increase forecast susceptibility to model climate “drift” and consequently biases are generally larger in long range forecasts and require calibration with hindcasts. Typically a set of hindcast integrations going back 20 years or more in the past is used to calibrate the sub-seasonal to seasonal predictions. The hindcast initialization relies on the capability of the re-analysis in providing consistent time series of data covering a sufficient long period of years. In this respect a general requirement for sub-seasonal to seasonal prediction is the availability of consistent historical observational data sets as well as a continuous provision of accurate observational data in the future.

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