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Simulating conditional deterministic predictability within ocean frontogenesis

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ABSTRACT

Ocean mesoscale eddies are non-deterministic in that small errors grow in time so that accurate prediction is not possible without continual correction from observations. Ocean frontogenesis can be forced by mesoscale eddies through straining of buoyancy gradients, which produces filaments of surface divergence related to ageostrophic upwelling. The upwelling can result in thinning of the mixed layer. The frontogenesis predictability is tested through a series of Observation System Experiments (OSEs), the results of which indicate that if the strength and location of the mesoscale eddies are accurately predicted, then the associated frontogenesis features can be predicted. The frontogenesis features have a 'conditional deterministic predictability'. The OSEs are started with perturbed initial conditions, and the OSEs assimilate an increasing number of satellite altimeter data streams. One experiment uses all available data to provide the most accurate analysis, which is labeled as the nature run. Relative to the nature run, ocean steric height correlations increases from about 0.87 with one altimeter and asymptotically reaches 0.99 with four altimeters, showing increasing skill in mesoscale prediction. Satellite data provide no information to dynamically correct frontogenesis processes in the numerical models. Even though not corrected by data, as the number of satellite altimeters increases from 1 to 4, the spatial correlation to the nature run of the frontogenesis forcing increases linearly from 0.27 to 0.59, the surface divergence correlation increases linearly from 0.27 to 0.57 and mixed layer depth correlation increases linearly from 0.67 to 0.89. The conclusion is that within the simulations the frontogenesis filaments are deterministically predictable conditioned on accurate prediction of the mesoscale.

1. Introduction

Mesoscale fronts associated with strong horizontal density gradients and geostrophically balanced velocity along these gradients are ubiquitous features of the upper ocean. The geostrophic flow strains the buoyancy field resulting in increasing horizontal buoyancy gradients that in turn act as a forcing to ageostrophic motions moving the front back towards a geostrophic balance. The confluence of water masses is a form of frontogenesis, which we will denote as mesoscale forced frontogenesis or deformation-induced frontogenesis (Hoskins and Bretherton, 1972; McWilliams et al., 2009a,b) to distinguish this form from other forms of frontogenesis. Associated with this class of frontogenesis are significant changes in the potential vorticity and vertical velocity. The association of the frontogenesis and potential vorticity changes has been observed *in situ* (Pollard and Regier, 1992; Pallàs-Sanz et al., 2010). The frontogenesis-driven upwelling can also result in filaments of shallow mixed layer depth (MLD) that occur along mesoscale fronts, such as the shallow MLD filament stretching from 125° E to 128° E along 21° 37′ N in Fig. 1. The filaments are 10 to 20 km across and hundreds of kilometers in length. The Western Pacific provides an attractive study area because this region encompasses several mesoscale eddies and fronts associated with the Kuroshio and deep Pacific Ocean, although such features commonly occur in other regions as well (Capet et al., 2008a). Filaments along eddy fronts have been transited by well instrumented ocean gliders in the northwest Mediterranean (Niewiadomska et al., 2008) and by shipboard surveys in the California Current System (Pallàs-Sanz et al., 2010), revealing that biological activity is associated with

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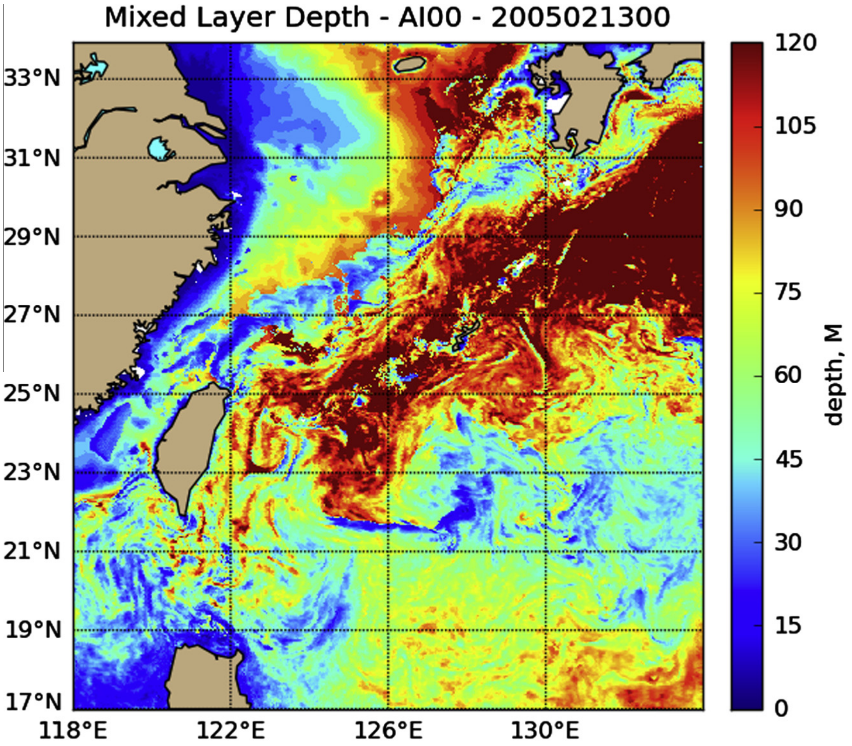

Fig. 1. A snapshot on February 6, 2005, of the model "nature run" mixed layer depth (MLD) with a filament featuring very shallow MLD approximately 20 km across and hundreds of kilometers long near (21° 37′ N, 125–128° E).

the vertical movement of water into the euphotic zone along fronts (Thomas et al., 2008).

The potential frontogenesis impact on the ocean (McWilliams et al., 2009a,b; Zhong and Bracco, 2013) motivates the question whether prediction systems have skill in forecasting filaments and their subsequent impact on the upper ocean and MLD. Prior theory (Hoskins, 1982) and studies (Pinot et al., 1996) have shown that one class of frontogenesis process is dynamically driven by the total derivative of the horizontal gradient of the buoyancy field. The buoyancy field and currents are primarily driven by the mesoscale field. As the mesoscale field strengthens horizontal buoyancy gradients, the forced ageostrophic motion results in vertical movement. Thus, given accurate knowledge of the mesoscale state, frontogenesis should be deterministic if a system is capable of representing the ageostrophic velocity response to the buoyancy straining generated by the mesoscale field. The objective at hand is to quantify the predictability related to frontogenesis and its effects with respect to present observing systems.

The Global Ocean Data Assimilation Experiment (GODAE) (Bell et al., 2009) provided several examples of ocean forecast capability built on numerical models that represent or at least permit the necessary mesoscale physical processes and the observation systems that provide continual corrections of the ocean state on a regularly cycling basis. An overview of the methods applied within the GODAE systems (Cummings et al., 2009) shows that the main objective of data assimilation is to regularly correct the mesoscale structure in the initial condition for the model forecast. Analysis increments in the temperature and salinity fields relate to changes in the velocity field through an assumption of a geostrophic balance, which is not the case for frontogenesis processes (Mensa et al., 2013). The present assimilation systems are not using observations to correct frontogenesis features. Satellite altimeter data are the major contributor to the ocean observing systems and the major source of information to constrain the mesoscale. Altimeter data do not contain significant signals from frontogenesis because the process occurs mainly in the upper ocean with little change in the sea surface height. Because frontogenesis is driven by mesoscale strain, the spatial scales are smaller than the mesoscale, and the spatial structures of the frontogenesis are not resolved by the altimeter ground track sampling patterns.

Taking these considerations together, present cycling forecast systems attempt to accurately correct the mesoscale field through assimilation of routine observations. If the physical processes of frontogenesis are represented properly within a numerical system, then a forecast model will generate frontogenesis in response to the mesoscale straining of the buoyancy field. Thus, the features have very little signal in observations, occur at scales not resolved by the observation system and are not dynamically corrected by the assimilation process, yet can be predicted. Previous studies have demonstrated that increasing the number of satellite altimeter observations leads to greater accuracy in forecasting the mesoscale features such as sea surface height (SSH) (Smedstad et al., 2003; Ananda et al., 2006). If the frontogenesis filaments are non-deterministic then prediction systems will not show skill regardless of the amount of altimeter data. If the filaments are purely deterministic then prediction systems will show skill even in the absence of assimilated data. If the filaments are conditionally deterministic then as data are added to the assimilation, both the mesoscale skill and frontogenesis skill will increase together.

A series of numerical experiments are analyzed to understand the impact of increasing altimetric sea surface height observations on the forecast skill at scales larger and smaller than the mesoscale and time periods shorter than 60 days. The results are consistent with the concept that the frontogenesis is deterministically driven by the mesoscale field within the simulations. As accuracy in the mesoscale field increases with increasing number of satellite altimeter observations, accuracy also increases in frontogenesis forcing, surface divergence and MLD. Thus the evidence supports the conclusion that filaments are conditionally deterministic. It should be cautioned that the context is within the simulation