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Climatic effects of mesoscale ocean–atmosphere interaction in an idealized coupled model

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Evidence is mounting that vigorous intrinsic variability associated with mesoscale oceanic features (with spatial scales on the order of 10–100 km) contributes significantly to large-scale low-frequency climate variability, with fundamental implications for near-term (~decadal) climate prediction. As of yet, extensive simulation of these decadal effects using high-resolution state-of-the-art coupled climate models has been computationally prohibitive, as it may require mesoscale-resolving atmospheric components. In this work, we study the effects of mesoscale air–sea coupling on large-scale low-frequency (interannual-to-decadal+) climate variability using the Quasi-Geostrophic Coupled Model (Q-GCM), in which the dynamical (QG) oceanic and atmospheric modules are coupled via interactive ageostrophic oceanic and atmospheric mixed layers. The key feature of this ageostrophic air–sea coupling is a temperature-dependent wind-stress, which permits effective transmission of the ocean induced sea-surface temperature anomalies to the free atmosphere. We perform multi-century Q-GCM simulations over a range of atmospheric and oceanic resolutions to identify parameter regimes of enhanced multi-scale ocean– atmosphere interaction and analyze their dynamics.

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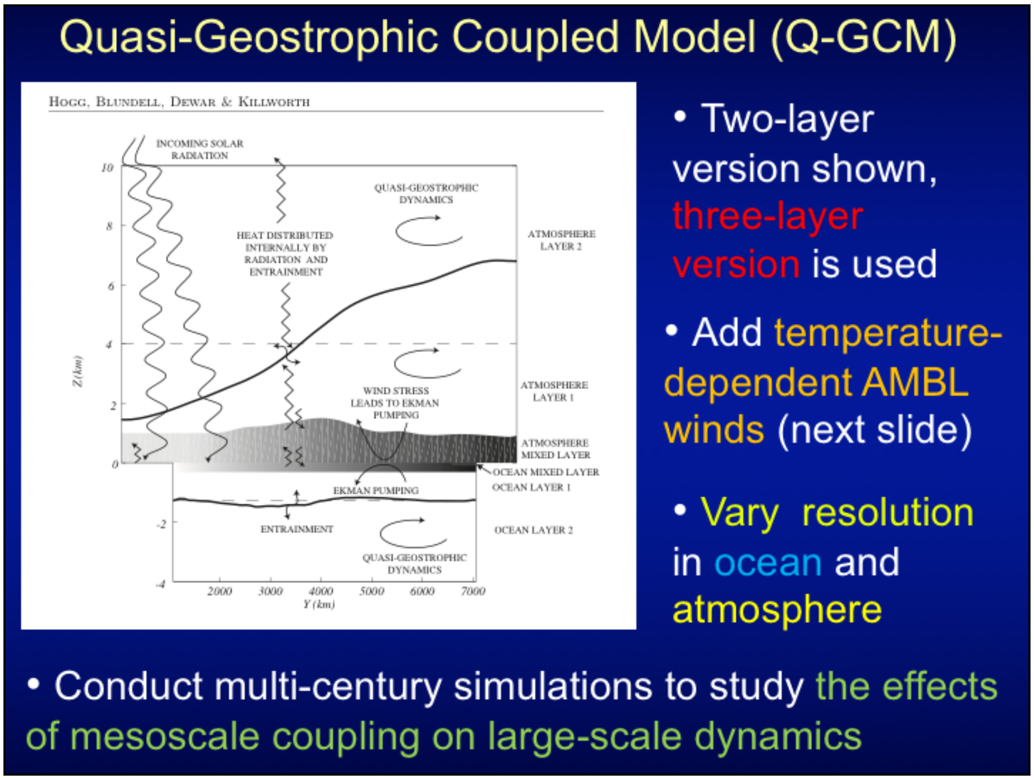
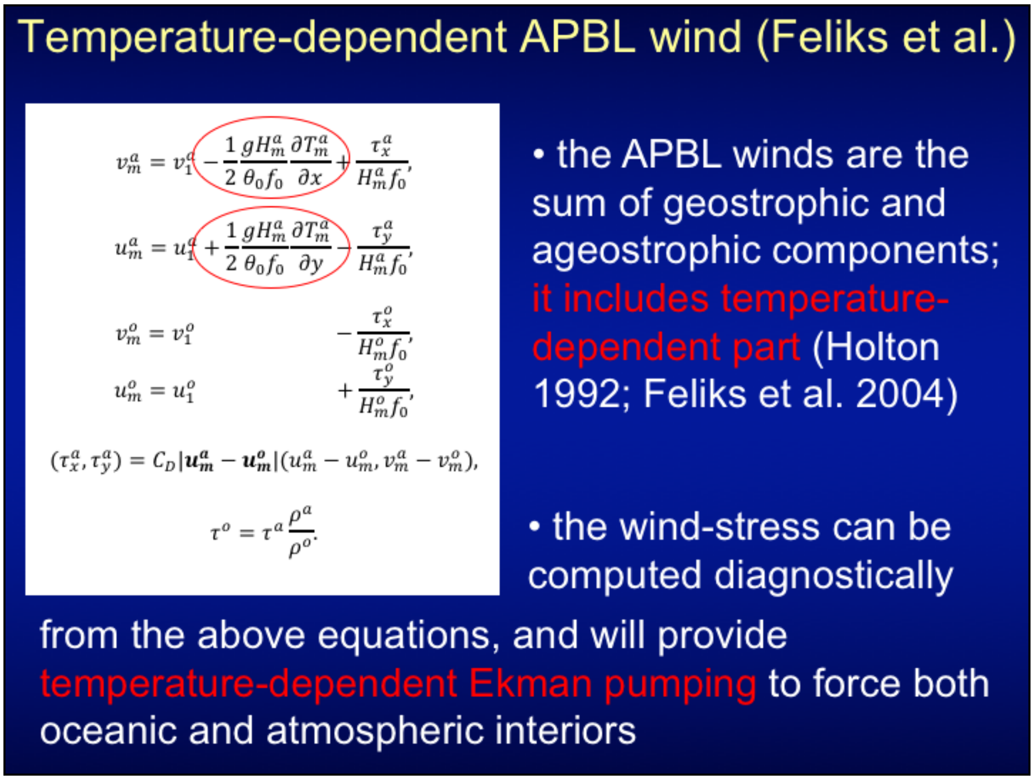


Schematic of (a two-layer version of) the Quasi-Geostrophic Coupled Model (Q-GCM; Hogg et al. 2003, 2006). This meridional slice through the model shows the interface dividing the two QG dynamical layers in both the ocean and the atmosphere. The (ageostrophic) mixed layers, shown by the shading which represents temperature, act to distribute heat and momentum between the two domains. The model is driven by latitudinally varying solar forcing and by redistribution of heat by longwave radiation in the atmosphere. Adapted from Fig. 1 of *Hogg et al*. [2014]. The model's latest distribution is publicly available from http://www.q-gcm.org, and features three-layer configuration in both fluids. We add a temperature dependent component to the atmospheric boundary layer winds (see below), and run multi-century simulations of the coupled model in the turbulent regime under both coarse and mesoscale-resolving atmospheric grid spacing.



Feliks et al. [2004, 2007, 2011] and *Brachet et al.* [2012] examined the response of the atmosphere to mesoscale sea-surface temperature (SST) anomalies through hydrostatic pressure adjustment in an idealized atmospheric model. They showed that resolving an ocean front and mesoscale eddies affects atmospheric climatology, intraseasonal modes, as well as decadal variability (when forced with the observed SST history) in their model [see also *Nakamura et al.*, 2008]. We include the Feliks et al. parameterization of the SST dependent ABPL boundary winds in the Q-GCM model, by modifying the atmospheric mixed-layer momentum equation accordingly. The SST front will tend to induce a similar front in the APBL temperature distribution, which will produce temperature-dependent wind stress and the associated pumping, forcing the oceanic and atmospheric QG interiors.

Temperature-dependent wind stress (Hogg et al.)

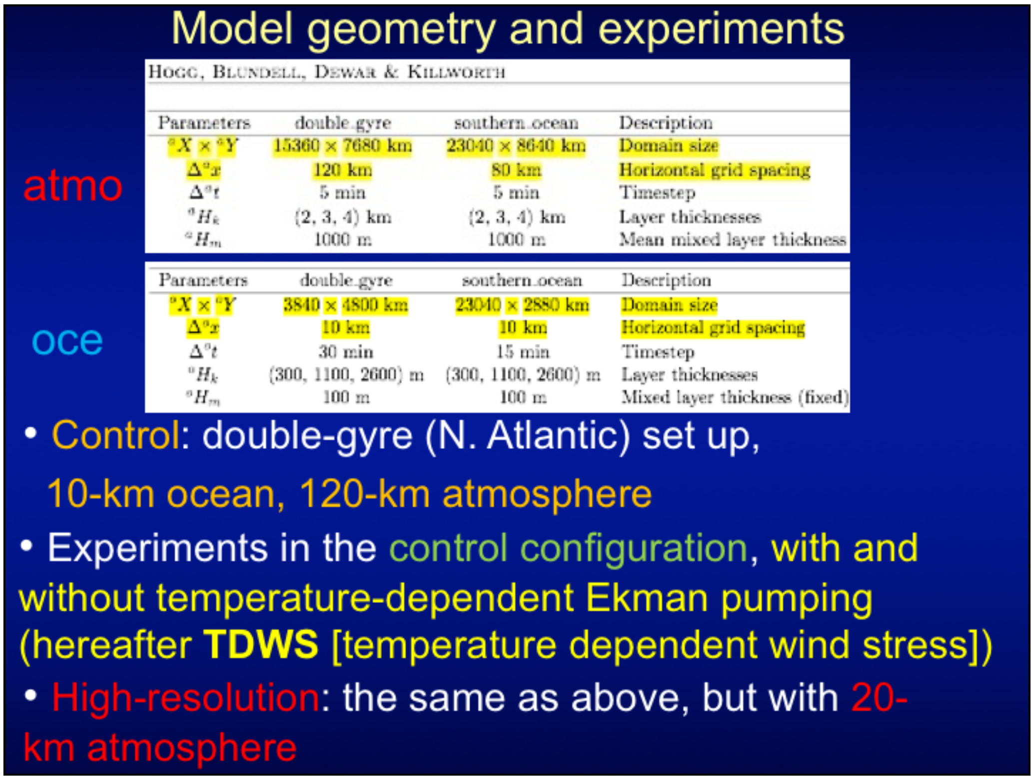
$$v_m^a = v_1^a + \frac{\tau_x^a}{H_m^a f_0},$$

$$u_m^a = u_1^a - \frac{\tau_y^a}{H_m^a f_0},$$

$$(\tau_x^a, \tau_y^a) = C_D\big(1 + \alpha(T_m^o - T_m^a)\big)|\boldsymbol{u}_m^a - \boldsymbol{u}_m^o|(u_m^a - u_m^o, v_m^a - v_m^o).$$

- Another (heuristic) way of parameterizing the effects of mesoscale SST gradients on the atmosphere above was suggested by Hogg et al. (2009)
- Here the wind-stress is assumed to be proportional to the ocean–atmosphere temperature difference (aligned, at mesoscale, with ocean-induced SST anomalies)

Another way of incorporating the mesoscale SST effects on the dynamics of air–sea coupling is via including SST dependence in the wind-stress drag coefficient. This effect may be present physically in the ‘real world’ too, but here its magnitude is substantially augmented to correspond, quantitatively, to the observed response of APBL winds to SST fronts (see below). Here, again, the temperature-dependent wind stress would produce large Ekman-pumping anomalies over mesoscale SST features (and the associated forcing of the circulation in the interiors of both fluids).

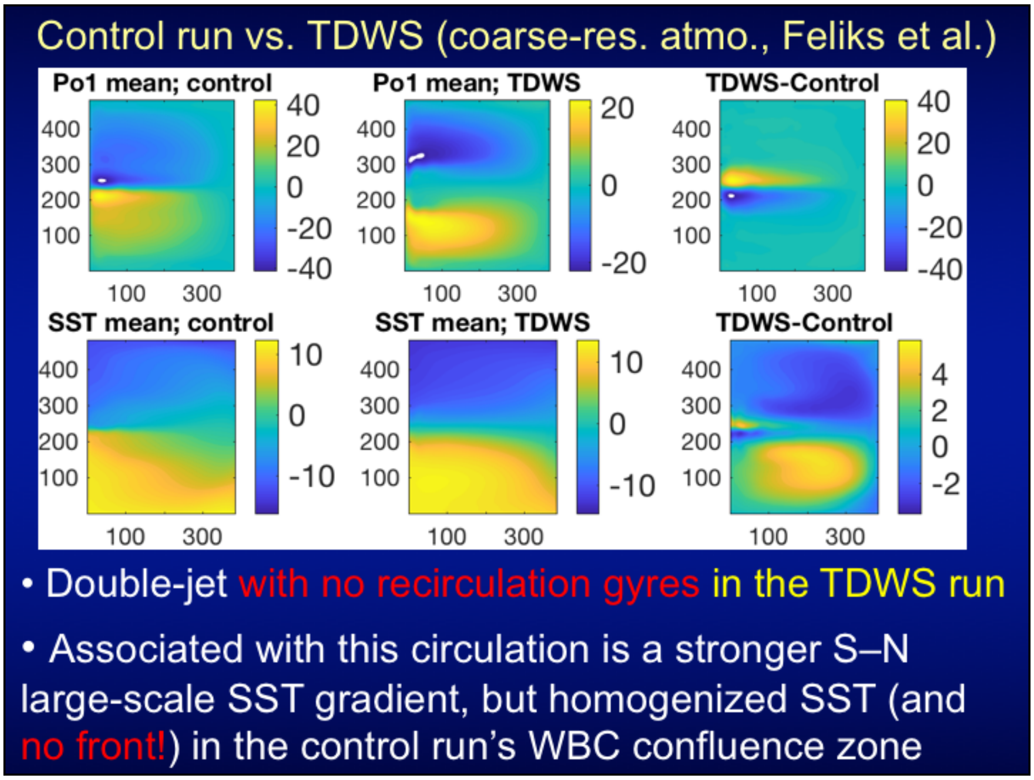


HOGG, BLUNDELL, DEWAR & KILLWORTH

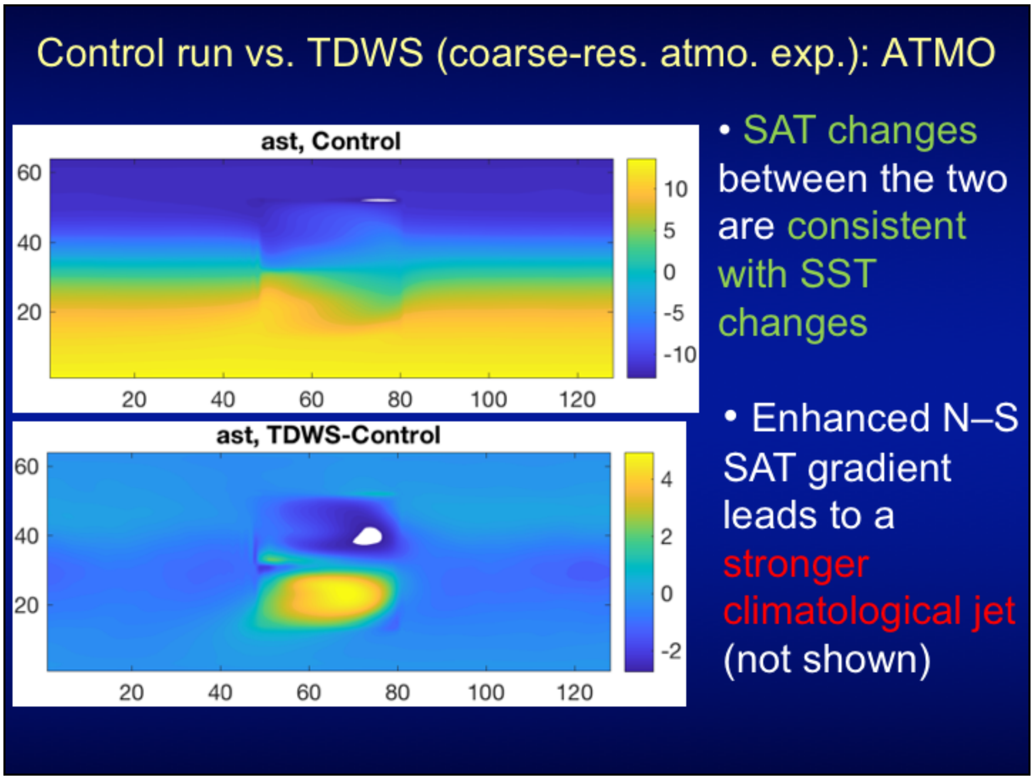
Parameters	double gyre	southern ocean	Description
${}^aX \times {}^aY$	15360 × 7680 km	23040 × 8640 km	Domain size
$\Delta^a x$	120 km	80 km	Horizontal grid spacing
$\Delta^a t$	5 min	5 min	Timestep
${}^aH_k$	(2, 3, 4) km	(2, 3, 4) km	Layer thicknesses
${}^aH_m$	1000 m	1000 m	Mean mixed layer thickness

Parameters	double gyre	southern ocean	Description
${}^oX \times {}^oY$	3840 × 4800 km	23040 × 2880 km	Domain size
$\Delta^o x$	10 km	10 km	Horizontal grid spacing
$\Delta^o t$	30 min	15 min	Timestep
${}^oH_k$	(300, 1100, 2600) m	(300, 1100, 2600) m	Layer thicknesses
${}^oH_m$	100 m	100 m	Mixed layer thickness (fixed)

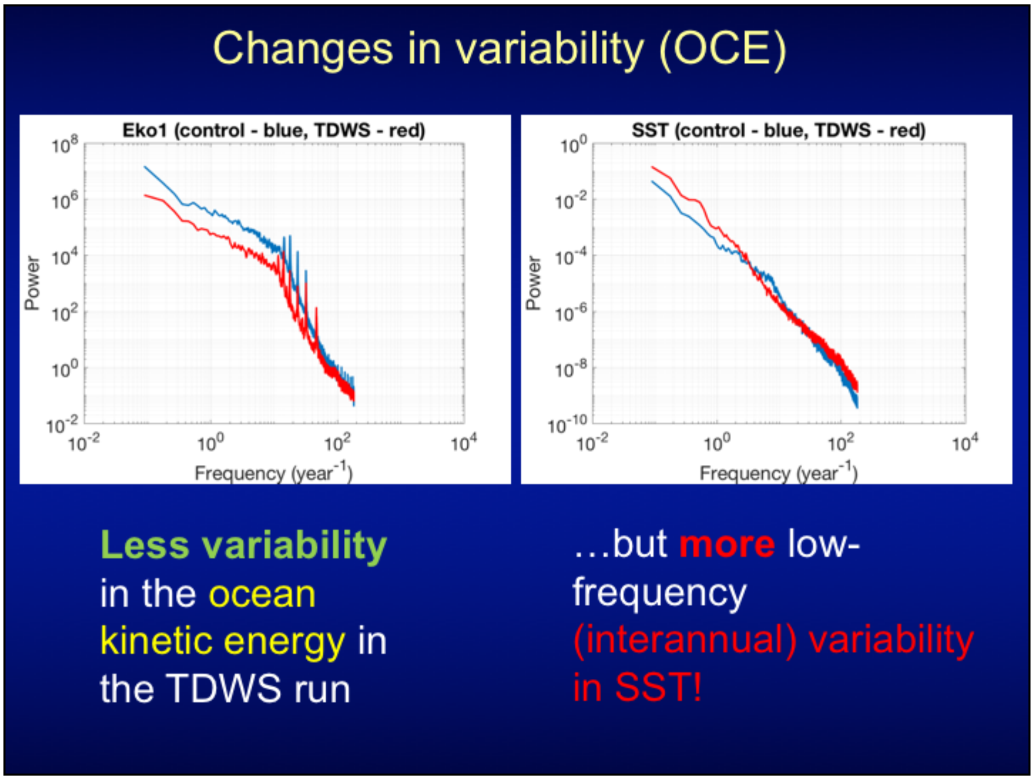
We perform multi-century model simulations in the double-gyre (North Atlantic ocean box) configuration, fixing the ocean resolution at 10 km and varying atmospheric resolution from 120 km in the control runs to 20 km in the high-resolution runs (horizontal viscosities and diffusivities adjusted accordingly to provide numerical stability). First, we run twin control experiments with and without temperature-dependent wind stress – hereafter, **TDWS** (and coarse atmospheric resolution in both). Then we repeat these experiments in the model with high-resolution (20-km) atmosphere.



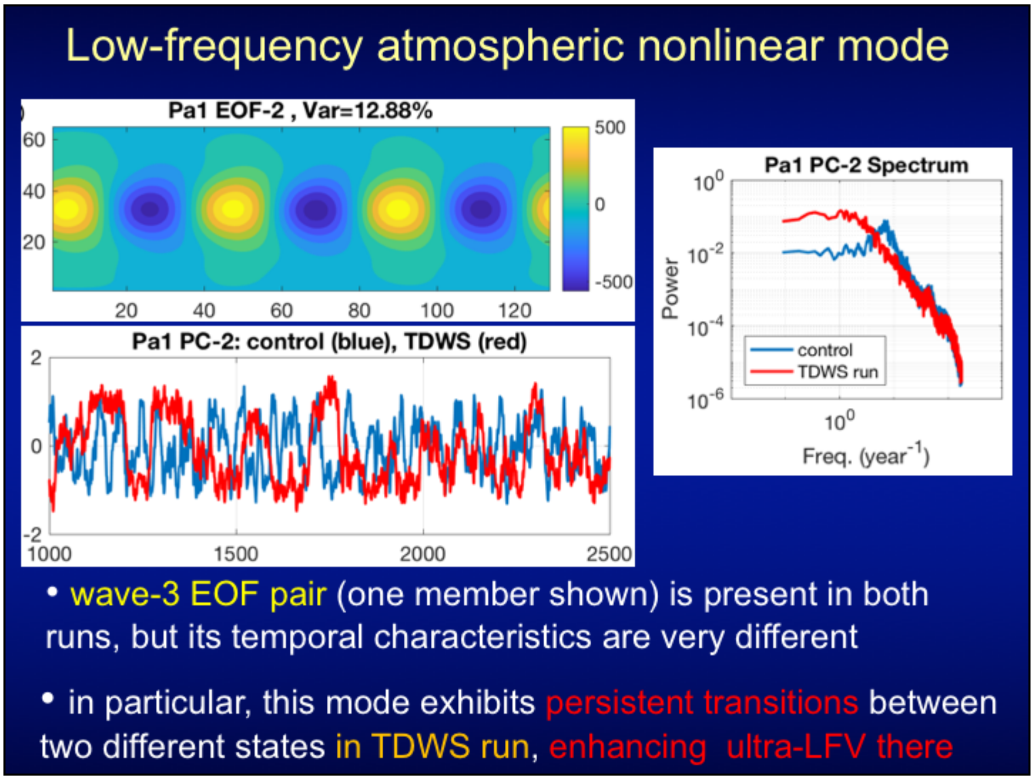
We start by comparing the experiments with and without TDWS parameterization in the control configuration with low-resolution atmosphere. Shown here is the climatology of oceanic streamfunction (Sv) (top) and SST (degrees C) (bottom) in both runs, as well as their difference. The mesoscale air–sea coupling (with Feliks et al. parameterization in this case) leads to weaker oceanic turbulence resulting in a quite different oceanic climatology compared to the control run. In particular, the pronounced inertial recirculations evident in the control run are damped in the TDWS simulation, along with the associated SST front. Large-scale north–south SST gradients in the TDWS run are, however, stronger. These results are consistent with previous work: mesoscale perturbations in SST will affect the atmospheric winds, which in turn feed back onto the ocean through perturbation heat fluxes [e.g., *Nonaka and Xie*, 2003; *Xie*, 2004; *Jin et al.*, 2009) and Ekman pumping [*Stern*, 1965; *McGillicuddy et al.*, 2007; *Dewar and Flierl*, 1987; *Maloney and Chelton*, 2006; *Gaube et al.*, 2013, 2015; *Chelton*, 2013; *Small et al.*, 2014]. These feedbacks are negative, as they tend to reduce the intensity of the oceanic mesoscale perturbations that generated the wind anomalies in the first place. Hogg et al. (2009) speculated that the TDWS effect on oceanic eddy activity is indirect and occurs via modifications of western boundary current stability characteristics.



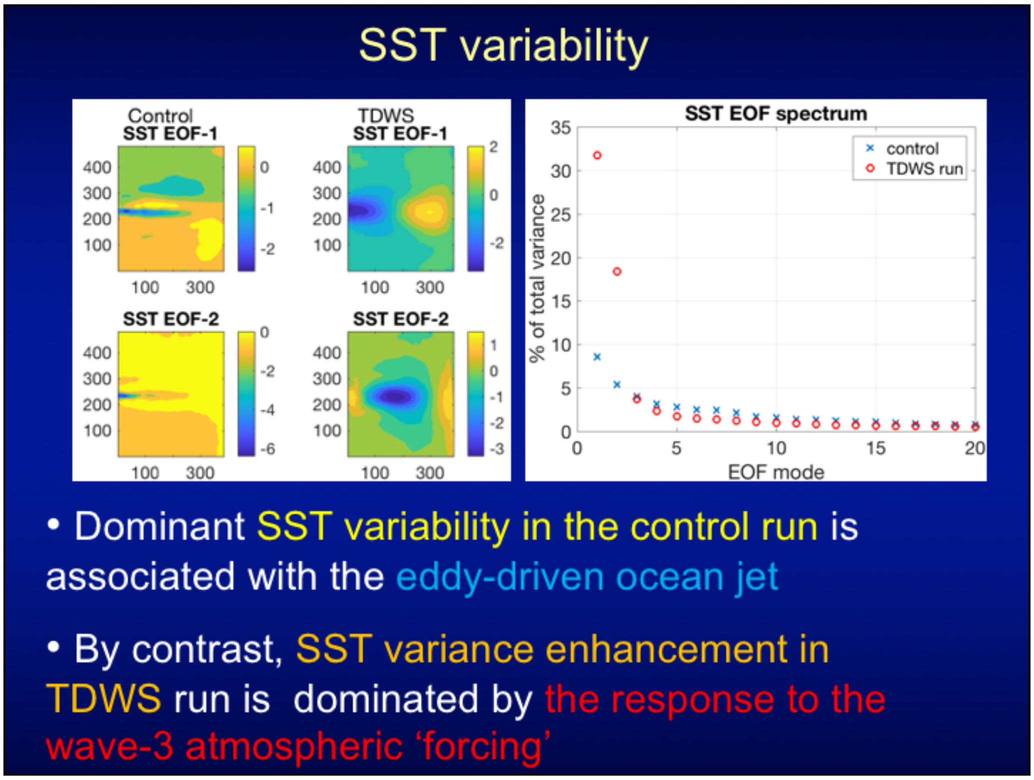
Substantial changes in atmospheric climatology also arise, consistent with the changes in the oceanic circulation and SST.



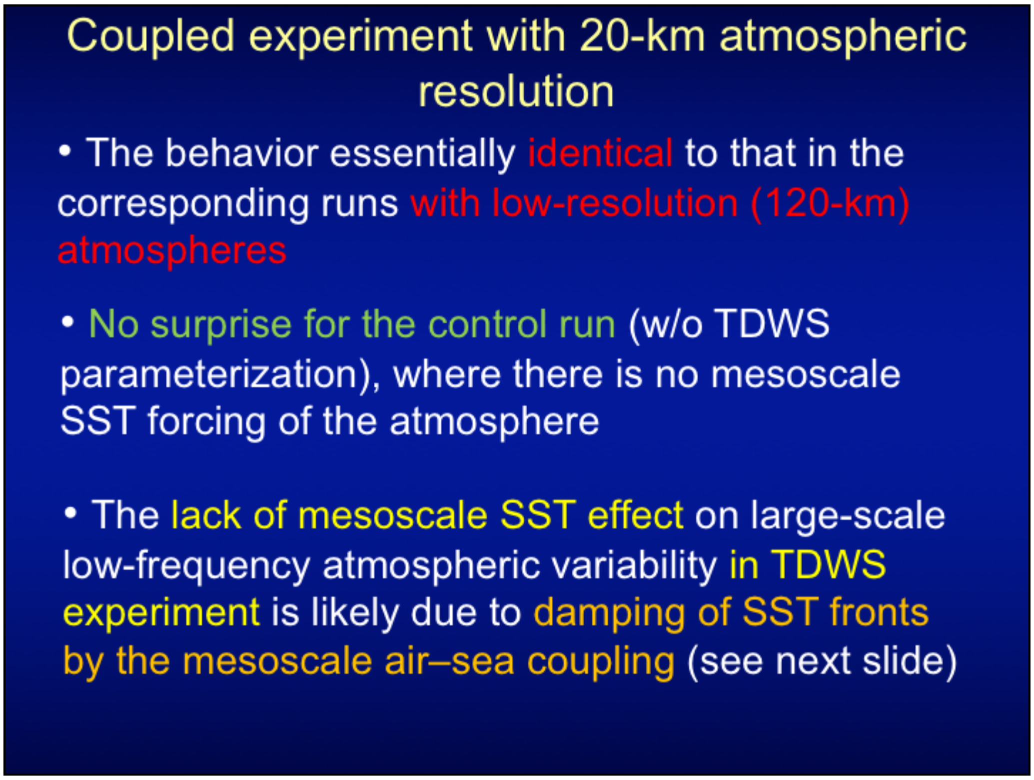
Ocean kinetic energy (left) is lower in the TDWS run, consistent with muted mid-latitude ocean jet and less overall ocean turbulence. However, the low-frequency SST variability in the TDWS run is **enhanced**! This enhancement is due to a fundamental change in the character of the atmospheric low-frequency variability in the simulation with temperature-dependent (Feliks et al.) currents in the atmospheric mixed layer (see below).



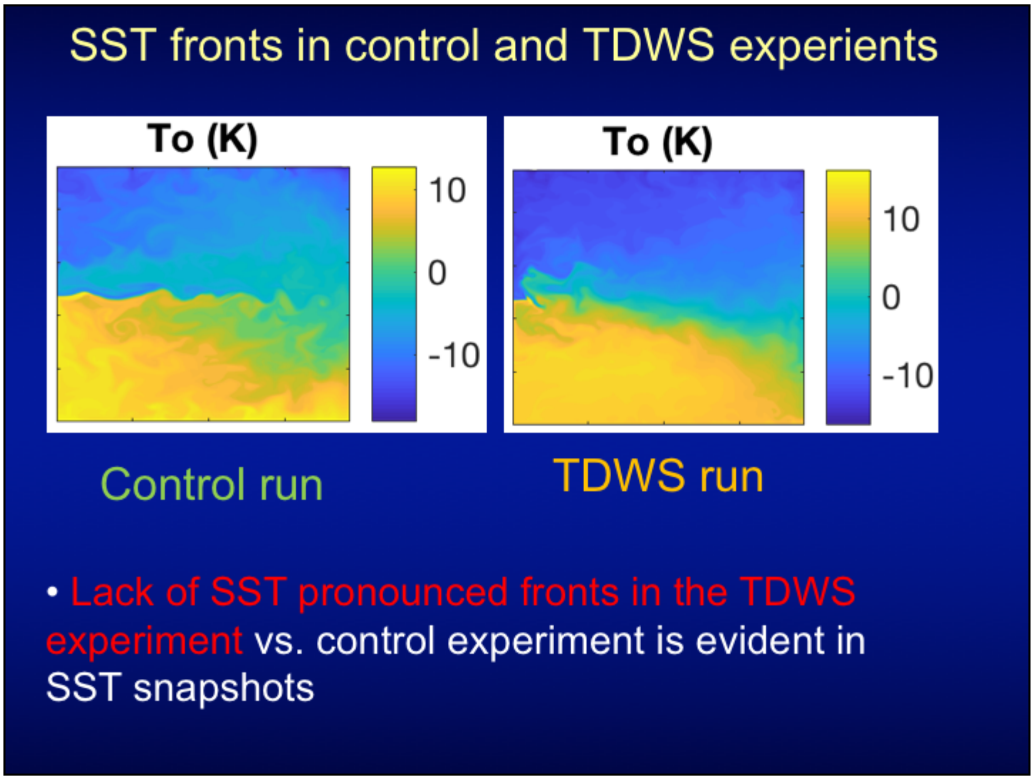
The changes in the atmospheric variability between control and TDWS runs are dominated by the behavior of the wave-3 EOF pair. Evident are persistent switches of this mode's PC time series between different regimes, which results in much more intermittency and a low-frequency spectral enhancement in the TDWS run.



Control run oceanic EOFs are dominated, once again, by eddies around the climatological jet, while the leading EOFs of the TDWS run reflect, most likely, large-scale response to atmospheric anomalies. In particular, EOFs 1 and 2 (which sharply dominate the EOF spectrum in TDWS run), are clearly forced by the intermittent low-frequency wavenumber-3 patterns identified in previous slide. The enhancement of the lower-frequency atmospheric variability in the TDWS run is thus not associated with the more efficient transfer of the ocean-induced low-frequency anomalies to the atmosphere, but rather with the combination of SST memory and atmospheric nonlinear dynamics leading to the emergence of low-frequency regime transitions associated with wave-3 atmospheric mode.



Analogous experiments with 20-km–resolution atmosphere produced the behavior essentially identical to that in the corresponding runs with coarse-resolution (120-km) atmosphere. This was to be expected for the control experiment w/o TDWS parameterization, in which the Ekman pumping from APBL does not ‘see’ mesoscale SST gradients. On the other hand, in the experiment with Feliks et al. TDWS parameterization, the absence of the mesoscale SST effect onto the atmospheric variability is most likely due to damping of oceanic turbulence and SST fronts by the mesoscale air–sea coupling, as per the discussion in the previous slides.



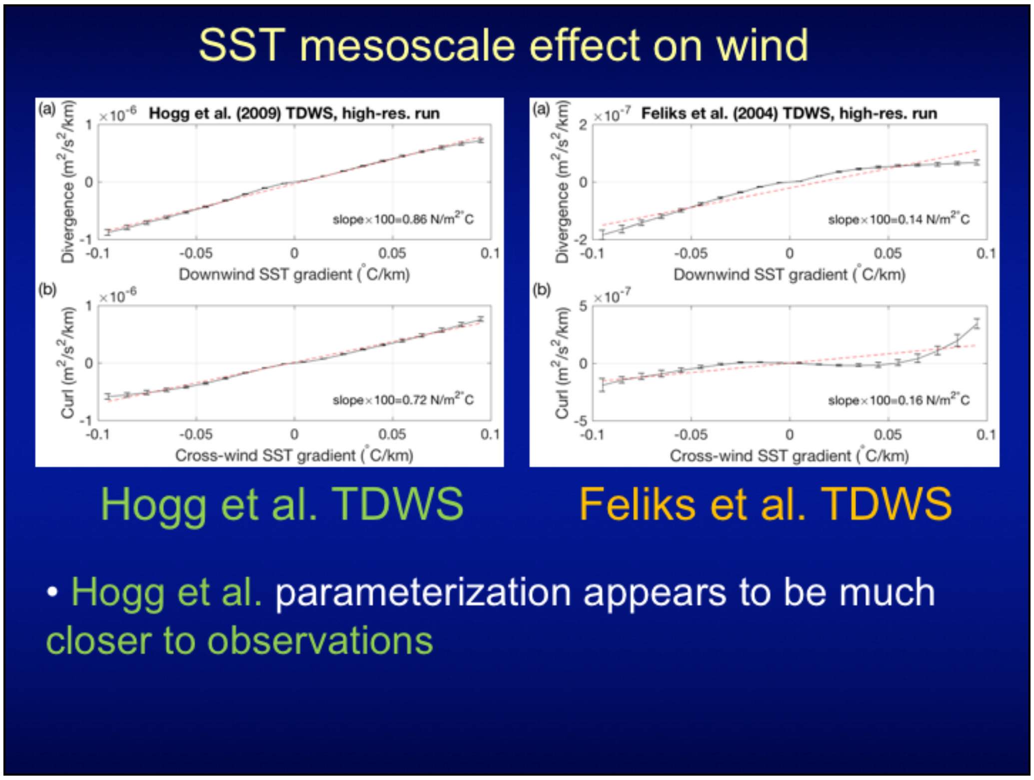
Typical snapshots of SST from the control run and TDWS run demonstrate the lack of pronounced SST fronts in the latter experiment. Reduced and disorganized mesoscale SST gradients preclude the effective mesoscale communication between APBL and overlying free atmosphere even in the experiments with high-resolution atmosphere (see previous slide).

Experiments with Hogg et al. TDWS parameterization

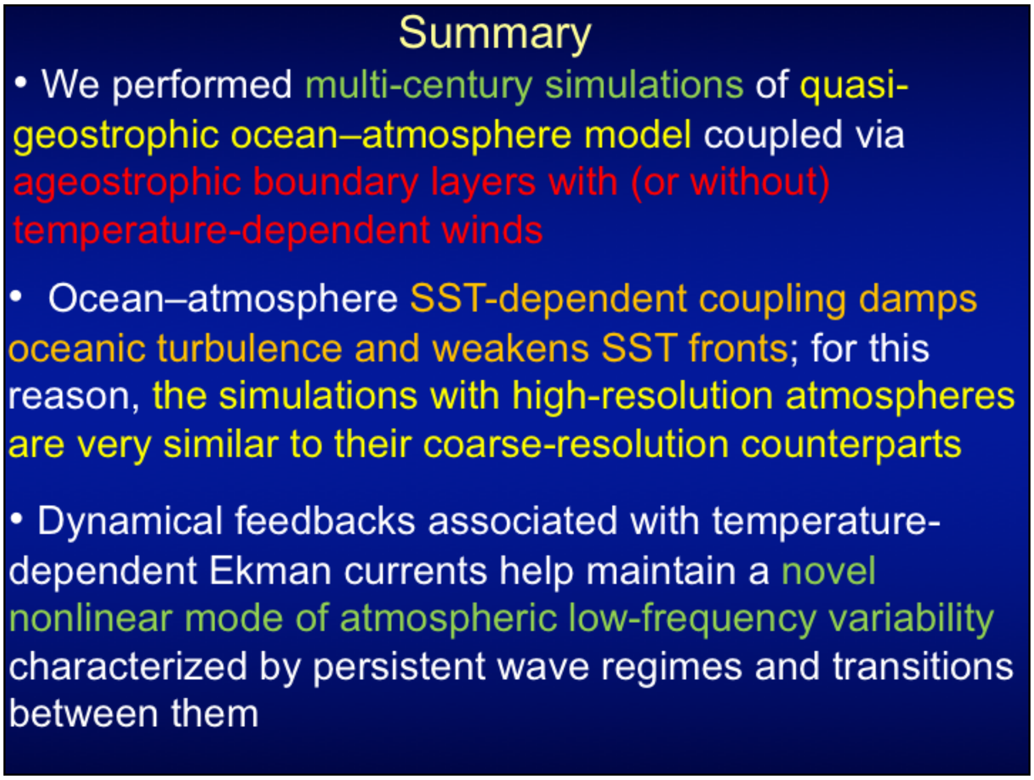
- Coarse resolution atmosphere: the same damping of oceanic turbulence and SST fronts in the TDWS experiment relative to the control experiment; no change in the atmospheric mean state and variability between the two runs (so no internal ultra-LFV mode present in TDWS runs with Feliks et al. parameterization)

- High-resolution atmosphere: once again, the same behavior as in the corresponding runs with coarse atmospheric resolution, likely due to damping of oceanic mesoscale variability by mesoscale air–sea coupling

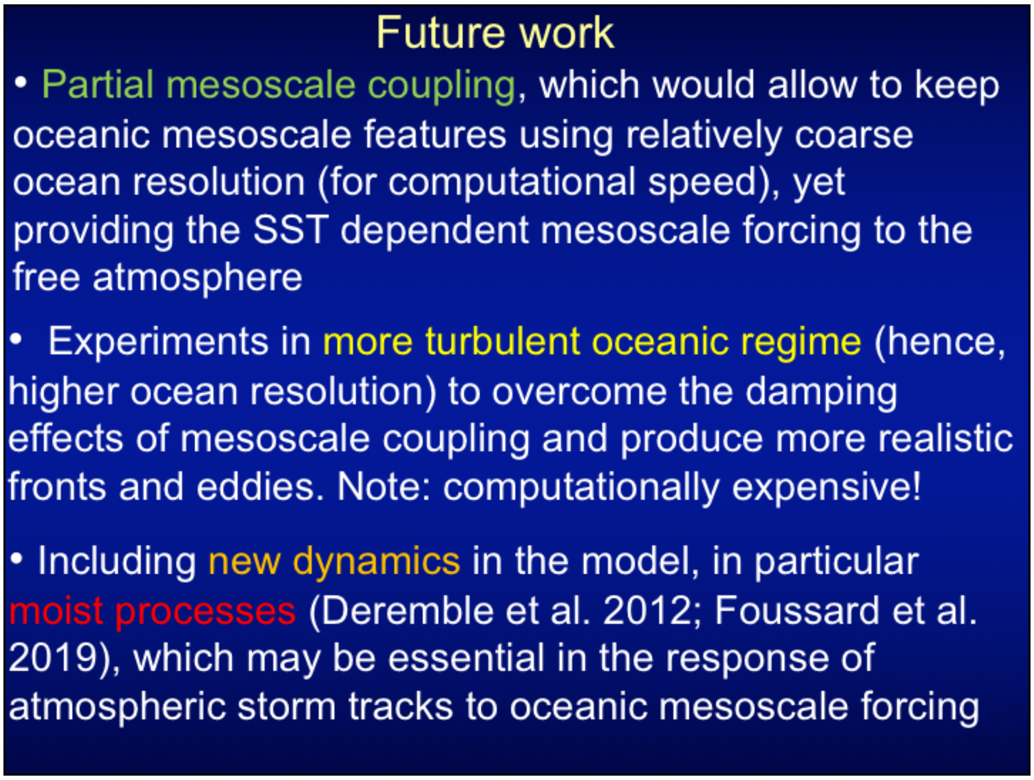
The results of the experiments with an alternative ad-hoc TDWS parameterization of Hogg et al. (2009) produced similar results with regards to mesoscale air–sea coupling. This parameterization produces similar dynamical feedbacks onto the oceanic mean circulation and variability, by damping the oceanic turbulence and SST fronts (not shown). In this case, however, there is also no amplification of nonlinear atmospheric variability due to the inclusion of temperature dependence in the atmospheric boundary-layer dynamics (as in the runs with Feliks et al. parameterization), and the atmospheric mean state and variability of the coarse-atmo-resolution experiments with and without TDWS are very similar. Damping of ocean eddies and SST fronts leaves no way for mesoscale air–sea coupling to become more important in the high-atmo-resolution experiments and, indeed, the variability in these runs is essentially the same with that in the corresponding coarse-atmo-resolution experiments.



To complete the comparison of the two types of the TDWS parameterization in our coupled experiments, we estimated the effect of SST gradients on the model's APBL winds. A number of studies have shown a linear correlation between downwind (cross-wind) SST gradients and wind stress divergence (curl) (Chelton et al. 2001; O'Neill et al. 2003; Chelton et al. 2004; O'Neill et al. 2005). We computed these dependencies following the procedure established by Chelton et al. (2001) and adopted by Hogg et al. (2009) for Q-GCM simulations. Here we used 150-yr output of the high-res. simulations with Hogg et al. (2009) and Feliks et al. (2004) TDWS parameterizations. We divided the data into 10-yr segments, spatially filtered to concentrate on mesoscale anomalies, and used the downwind (crosswind) temperature gradient at each data point to divide the wind stress divergence (curl) into bins and find the average within each bin. The same procedure applies to each 10-yr segment, after which the mean and standard deviation of the 15 segments can be found. The resulting dependencies from the simulation with Hogg et al. (2009) parameterization bear striking qualitative and quantitative similarity with observations, which manifest linear relationships with similar slopes (for example, the slope of the divergence plot is 0.86, compared to 0.96 for the Kuroshio and 1.09 for the Gulf Stream; Chelton et al. 2004). On the other hand, these dependencies in the simulation with Feliks et al. (2004) TDWS parameterization are nonlinear and much too weak.



It was shown before (*Feliks et al.* [2004, 2007, 2011]; *Brachet et al.* [2012]) that the free atmosphere can be quite sensitive to the time-dependent mesoscale SST features, which motivated the present quest to search for novel coupled ocean–atmosphere modes maintained by multi-scale coupling between the two fluids. The key message from our work thus far is that this search in a coupled setting is complicated by the substantial damping of oceanic mesoscale features by the wind anomalies generated by the mesoscale air–sea interaction — the same anomalies that supposedly trigger the large-scale atmospheric response reported on previously. Possible avenues for further investigation of this issue are outlined in the next slide.



We are currently in the process of performing extensive parameter sensitivity checks of the TDWS parameterizations in the atmosphere-only setting forced by the imposed SST fronts and eddies. These experiments will pave the way for further coupled experimentation, along the directions outlined in this slide.

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The reference list on this topic is extensive. Just a few representative references are given in this slide and the next.

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