Simulating pancake and frazil ice growth in the Weddell Sea: A process model from freezing to consolidation

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[1] Processes controlling the formation and transformation of frazil to pancake ice are examined using data from an array of drifting buoys deployed at the advancing ice edge in the Weddell Sea. A simple thermodynamic model is coupled to the buoy dynamics and to an ice redistribution model to determine the influence of deformation, thermodynamics, and mechanical scavenging, incorporating frazil crystals from the surrounding slick into the pancakes, on the partitioning of ice volume between frazil and pancakes. Ice production was examined from the time the buoys were deployed until the frazil/pancake cover consolidated into the more familiar pack ice. The model reproduced the expected ice cover thickness at consolidation (60 cm). Rafting was the dominant contribution to thickening in the region owing to large-scale compression of the initial area by northerly winds from passing low-pressure weather systems, which are rather typical in the region. High-resolution positional forcing from the buoys (20-min intervals) doubled the contribution of mechanical scavenging to final pancake thickness compared to the coarser (2-h) result, owing to the larger path length that the pancakes traverse through the frazil slick, and produced a significantly larger volume of ice in the pancake phase. The ice cover generated at consolidation was approximately twice as thick as would have formed by the more familiar congelation ice growth under the same forcing, reinforcing the importance of correctly parameterizing the early stages of ice formation in the Antarctic. The study highlighted uncertainties in the effect of the frazil/pancake cover on ocean-atmosphere heat exchange, both in terms of the area contributing to ice production and the effect on turbulent exchange coefficients. Further work placing the empirical parameters into a more constrained physical framework and introducing wave properties is suggested.

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1. Introduction

[2] The Antarctic sea ice cover grows northward in winter into an environment dominated by the considerable wave energy of the Southern Ocean. The high levels of turbulence at the sea surface do not allow the ice to grow as solid sheets (termed congelation ice), as is the case for protected waters, but instead forms a suspension of small ice crystals, termed frazil or grease ice. These gradually freeze together into small agglomerations, termed pancakes, whose dimensions are controlled by the wavelength, λ, of waves traveling through them; studies suggest a diameter of 0.01λ to be typical [*Leonard et al.*, 1998a). The pancakes are surrounded by the remaining frazil slick and progressively incorporate more crystals into their structure, either by lateral or bottom-freezing, or by scavenging frazil crystals onto their surface as they move in the wavefield (see *Doble et al.* [2003]; hereinafter referred to as DCW03). The wavelength/pancake size relation continues to evolve as the shortest waves are damped in their progress through the ice, until pancakes of more than 5 m diameter and 50 cm thickness are observed. Eventually, wave energy is damped enough to allow the pancakes to freeze together into a continuous sheet, termed "consolidation." The unconsolidated pancake ice zone is typically 100–200 km wide at the ice edge and is the dominant influence on the thickness of the Antarctic sea ice cover [*Lange and Eicken*, 1991] since high oceanic heat fluxes generally prevent further appreciable thickening by thermodynamic growth [*Wadhams et al.*, 1987].

[3] Ice forms considerably faster in the frazil/pancake region than would be the case for a congelation ice sheet [*Squire*, 1998] since the ocean remains in contact with the overlying cold atmosphere. It is therefore critical to understand the processes occurring in this region if we are to correctly assess such large-scale parameters as ocean-atmosphere heat flux and salt input to the ocean, in pursuit

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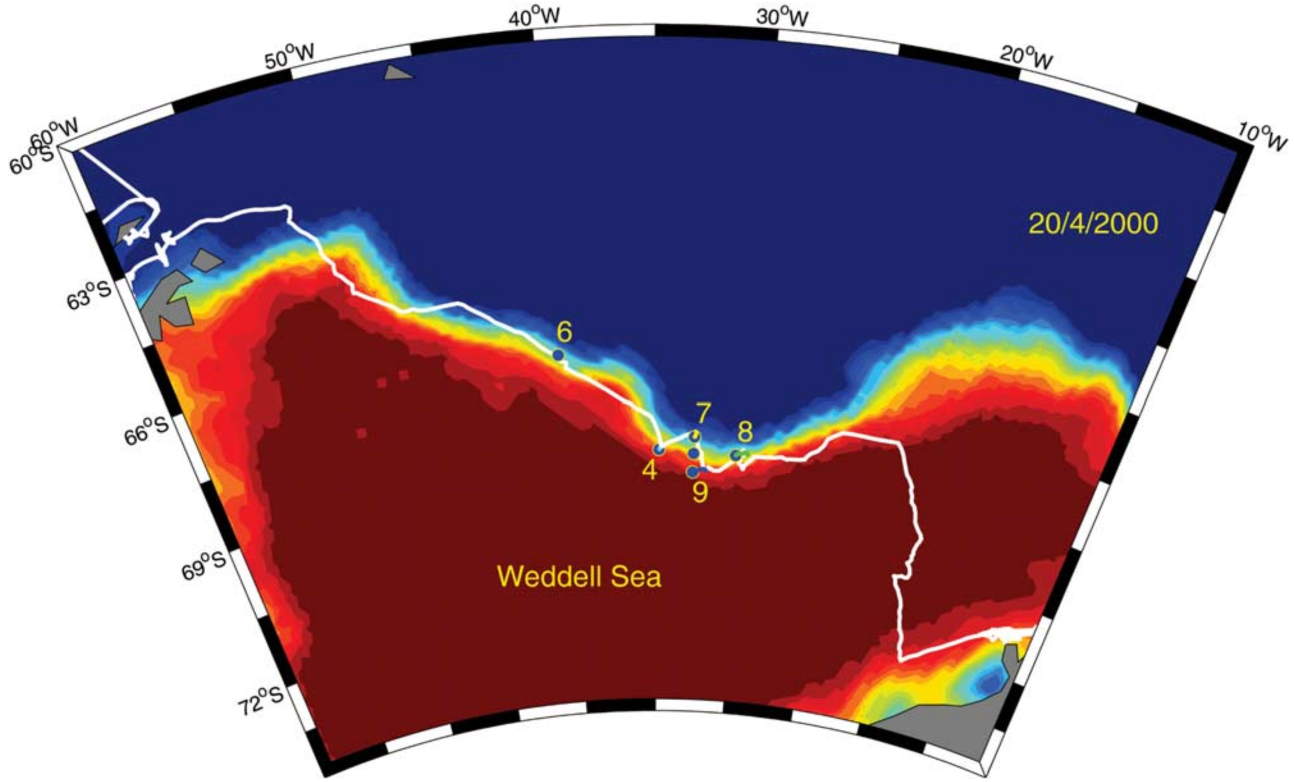

Figure 1. Buoy deployment locations superimposed on ice concentration percentage on 20 April 2000, derived from passive microwave data using the Danish Technical University algorithm. Shown in white is the cruise track of the deploying icebreaker *Polarstern*.

of improved large-scale models for forecasting or climate research objectives.

[4] Unfortunately, there is a dearth of field data from such regions, since the nature of the ice cover makes it difficult to study either with in situ instrumentation or by satellite remote sensing. Field experiments are limited to drifting buoy deployments into the Odden region of the Greenland Sea (one of the few occurrences of significant areas of pancake ice in the northern hemisphere) in 1997 [*Wilkinson and Wadhams*, 2003] and the data used in the current study; sampling and drifting buoy deployments carried out from the icebreaker *Polarstern* at six locations in the unconsolidated pancake zone of the Weddell Sea, in 2000 (Figure 1). The 2000 data was used to determine pancake formation rates and mechanisms (DCW03) and examine the changing dynamics as the ice cover consolidated (see *Doble and Wadhams* [2006]; hereinafter referred to as DW06). Good agreement was found between Odden and Weddell studies for dynamical parameters (wind factor and turning angle), suggesting global applicability for advection simulations. *Pedersen and Coon* [2004] used the 1997 data to develop a model for pancake ice production on the basis of local winds and an empirical ‘‘lead width’’ parameter.

[5] Other studies have focused on theoretical or ice tank experiments, though these latter investigations are not able to reproduce the scales of motion experienced in the field. Theoretical work has concentrated on action of waves on pancakes, variously advection [*Hopkins and Shen*, 2001], bending failure [*Shen et al.*, 2001] or wave-induced rafting against a fixed barrier [*Dai et al.*, 2004]. This last case is not generally encountered in the Antarctic since wave energy has by definition decayed below the level required for rafting once a fixed barrier (the pack ice) is encountered.

[6] In the present study, the Weddell Sea data are used to describe and parameterize several processes unique to the formation of frazil/pancake ice, using a simple 1-D thermodynamic model (developed in the work of DCW03) coupled to an ice redistribution model driven by the dynamics calculated in the work of DW06. The aim is to gain an appreciation both of the relative importance of processes which are not routinely discussed in the literature, and to examine the degree to which a simple congelation-based parameterization (such as that used in global models) underestimates total ice production in the circum-Antarctic pancake zone.

[7] The period between deployment of the buoys (16–19 April 2000) and the consolidation of the ice around the most northerly buoys (3 May 2000) is examined. Ice conditions during deployment are known (see DCW03 for details), and the buoys tracked the ice motion (GPS position) and measured meteorological parameters (air temperature, wind speed) and wave spectra.

[8] The buoys were deployed in a region which had recently experienced two cold-air outbreaks (as determined from ECMWF reanalysis), each of which was found to have created distinct layers in the pancake ice. The bottom layer of the pancakes was formed by accretion of frazil crystals in the accepted manner, while the top layer of each pancake was formed later by the rafting of frazil crystals on top of existing pancakes or congelation ice fragments. Only the

growth by this latter mechanism, termed "scavenging," is considered here since DCW03 demonstrated this to be far more efficient than bottom-layer growth and scavenging is therefore expected to dominate further thickening.

[9] The frazil/pancake model is first described, together with several simplifying assumptions. An empirical parameterization for the scavenging process is next developed. Other processes occurring in the frazil/pancake matrix are then discussed, together with their treatment in the model. Results are examined in terms of total ice production, the resulting balance between pancake and frazil ice volumes and the relative importance of the various processes involved. The pancake thickness at consolidation predicted by the model is compared with previous field results.

[10] The unconsolidated phase of the buoy drifts was found to exhibit a high-amplitude, high-frequency (20-min period) oscillation, which ceased immediately the pancakes consolidated into a continuous ice sheet (DW06). Its effect on the modeled ice thicknesses is examined by applying positional forcing at various resolutions. Shortcomings of the model and the need for further quantitative measurements are then discussed.

[11] Ice production throughout the paper is referred to in terms of "solid ice equivalent" (SIE), which takes into account measured volume concentrations of frazil ice (0.4) and pancake ice (0.7), simplifying the transformation between the two ice types.

2. Frazil/Pancake Model

2.1. Model Description

[12] Heat exchange between the ocean and atmosphere, and the resulting ice formation, was modeled using a simple 1-D energy balance model coupled to modules which tracked several novel processes controlling the transformation between frazil and pancake ice. The spatial domain of the model is that enclosed by the deployed buoys, with the change in area of the array being calculated by the line integral method, described in the work of *Lindsay* [2002]. Starting area of the array was 1800 km^2, reducing to 500 km^2 at consolidation. Convergence thus plays a dominant role in the ice dynamics for this test case.

[13] The thermodynamic component was described in DCW03 and is similar to previous frazil production models [e.g., *Martin and Kaufmann*, 1981; *Markus et al.*, 1998]. The main difference to more familiar congelation ice models is the absence of conduction terms within the ice, and the fact that the thickening frazil ice layer does not reduce the ocean-atmosphere heat flux since the liquid ocean remains in contact with the air.

[14] Forcing is variously taken from the in situ buoys (position, air temperature, wind speed), from the *Polarstern* when she was in the area and from ECMWF re-analysis fields when neither source of in situ data was available, or for parameters not measured in situ (e.g., cloud cover).

[15] Parameterization of processes within the frazil/pancake matrix relies on several simplifying assumptions:

[16] 1. The thickening of the pancakes' top layers only occurs by frazil scavenging owing to the pancakes' translation through the frazil slick. In fact it is expected that frazil scavenging also occurs as the pancakes tip in the wavefield and scoop frazil onto their top surfaces, but this does not present an objection given the phenomenological nature of the parameterization

[17] 2. Pancakes actually "travel through" the frazil ice surrounding them during their displacement, rather than the whole frazil-pancake matrix translating together. Observations suggest this is only partly true and this also contributes to the phenomenological nature of the parameterization

[18] 3. The area occupied by the pancakes does not contribute to ice production. Ice production only occurs in the interstitial frazil slick

[19] 4. Lateral growth of the pancakes, and hence reduction of area available for frazil production, is ignored. Observations suggest that this assumption is robust since (without large-scale compression and rarefaction) the areal partition between pancakes and frazil does not change significantly as they mature: for a given snapshot in time, the pancake area fractions were similar at all sampling stations and did not appear to be a function of pancake diameter, thickness or proximity to the consolidation boundary

[20] 5. The 20-min interval data captures all the pancake movement and no higher-frequency motions exist. This is a necessary assumption since no higher-frequency data exist, but is unlikely to be the case in the presence of waves. Any higher frequency motion is parameterized in the empirical value of the tuning parameters developed

[21] 6. It is assumed that no ice volume exchange occurs with the area surrounding the array: ice cannot be pushed outside the area enclosed by the array.

[22] The frazil scavenging process is first examined and a phenomenological parameterization of the process is derived. The empirically derived parameter is then used in a full dynamic-thermodynamic model.

2.1.1. Scavenging Efficiency: Transforming Frazil to Pancakes

[23] The second cold air outbreak (event 2) is considered since this was identified as the source of the pancake top layers, grown by frazil scavenging (DCW03). The thickness of ice transferred from frazil to pancakes by the scavenging process is given by:

$$h' = d.\Delta t.h_f.\varepsilon/f_p \tag{1}$$

where d is the amplitude of the oscillating array divergence, Δt is the timestep, h_f is the frazil slick thickness (SIE), ε is the scavenging efficiency, expressed as the fraction of frazil volume traversed that goes to thicken the pancakes through scavenging, and f_p is the area fraction of pancakes.

[24] It was established in the work of DCW03 that frazil slick available for building top layers had a thickness of 27 cm SIE at the beginning of event 2. If a 100% scavenging efficiency is assumed for the moment (i.e., all the frazil ice traversed by pancakes during the compression phase of the oscillation is scooped onto the surface of those pancakes) then during event 2, a volume of:

$$h' = 1.5 \times 10^{-5}.1200.\, 0.27.1/0.65 = 7.5 \text{ mm}$$

is scavenged during each (1200 s) cycle. The duration of event 2 (two days) represents 144 cycles of 20-min compression-rarifaction. Thickening of the pancakes owing

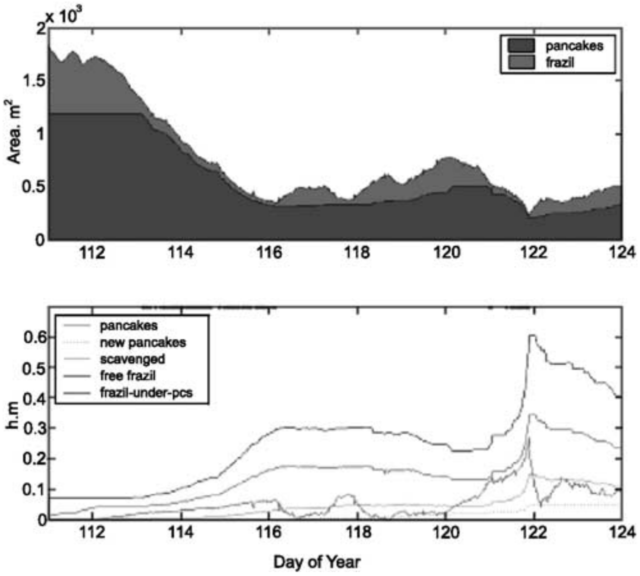

Figure 2. Output of the frazil/pancake redistribution model. (top) Areas of frazil and pancake ice. Positive steps in pancake area indicate the conversion of "aged" frazil to thin pancakes. A minimum fraction of 0.1 frazil is maintained in accordance with hexagonal close packing. (bottom) Solid ice equivalent thickness of pancakes indicating scavenged frazil ice and conversion from frazil. Also shown is the frazil slick SIE thickness between pancakes and underneath the whole area. Bold dots on the upper boundary of the bottom graph indicate that pancake rafting is taking place.

to compressive frazil scavenging is then $144 \times 7.5 \times 10^{-3} =$ 108 cm SIE, which is an order of magnitude more than observed (5 cm SIE). A simple estimate of the scavenging efficiency, ε, is thus 5/108 = 5%. Physically, this appears to be rather high, given the author's observations, but is a phenomenological value, subject to all the assumptions set out previously.

2.1.2. Redistribution Model

[25] The redistribution model tracks the areas and thicknesses of pancake and frazil ice enclosed by the array. The six assumptions detailed previously are maintained, and the model parameterizes the following processes:

[26] 1. Scavenging: while sufficient frazil area exists, pancakes scavenge frazil ice according to the following equation:

$$h'_p = h_p + \frac{\Delta A_f h_f \varepsilon}{A_p} \tag{2}$$

Where h_p is the pancake thickness, ΔA_f is the reduction in frazil area owing to convergence, h_f is the frazil slick thickness, ε is the scavenging efficiency, discussed above, and A_p is the area of pancake ice. The numerator represents the volume of scavenged frazil ice, equivalent to equation (1).

[27] 2. Compression: convergence reduces frazil area and thickens the frazil slick (and vice versa)

[28] 3. Packing: a minimum frazil area of 10% is maintained, dictated by the maximum hexagonal close packing of the (assumed) circular pancakes

[29] 4. Rafting: further convergence induces rafting of the pancakes. Though this is a discrete process (an individual pancake's thickness can only increase by multiples of the pancake thickness) the number of pancakes taking part in the rafting is variable, and this is indistinguishable in the model domain from fractional rafting.

[30] 5. Under-riding: if the frazil area is small and compression continues, then the frazil slick thickness between the pancakes will increase to very large values. Such a slick would greatly exceed the draft of the surrounding pancakes and in fact spread out underneath the pancakes to occupy their area as well. This is therefore allowed to occur in the model: the frazil volume is split into "interstitial frazil," which occupies the area between the pancakes to a maximum depth equal to the pancake thickness, and "deep frazil," which underlies the whole area. The partitions are tracked separately, with the frazil retreating from underneath the pancakes if the total slick thickness drops below the pancake draft. Volume fractions are accounted for when determining whether the frazil can under-ride the pancakes. Changes in the volume concentration of the frazil slick with depth are not parameterized since no reliable field measurements exist.

[31] 6. Transformation: during prolonged divergent events, the model creates large area fractions of frazil ice, which subsequently produce large volumes of ice and quickly result in unrealistically high frazil slick thicknesses. The model was therefore refined to mimic the transformation of frazil ice into pancakes seen in the field. Transformation into pancakes occurs if the frazil area exceeds a fixed percentage of the array area, taken as 35% in accordance with field observations. For a physical justification, it is suggested that smaller areas of frazil are disrupted by the existing pancakes traveling through them and are thus unable to consolidate into pancakes. A minimum time for the transformation to occur is also imposed: the age of frazil fractions exceeding the 35% threshold is tracked and transformation takes place once this "excess frazil" has exceeded an age threshold. A value of 24 h was chosen, as suggested by field observations, though it is likely to be a function of both air temperature and wave conditions. Once the age threshold is exceeded, 65% of that area is transformed into new pancakes of the observed initial 5 cm SIE thickness, having regard to volume fractions. If insufficient frazil volume is available (i.e., the slick is too thin), then the transformation still occurs but the new pancake thickness is adjusted accordingly. Total frazil and pancake volume is conserved during the transformations, with the partition between interstitial and deep frazil being adjusted before thermodynamic growth occurs in the timestep.

2.2. Results

2.2.1. Ice Production

[32] Model output is shown in Figure 2. The array area is initially divided between 35% frazil and 65% pancake ice, as observed during deployment of the buoys. The model can be initialized with simply open water and would rapidly generate an equivalent partition, following the aging/transformation processes. Compression quickly takes up

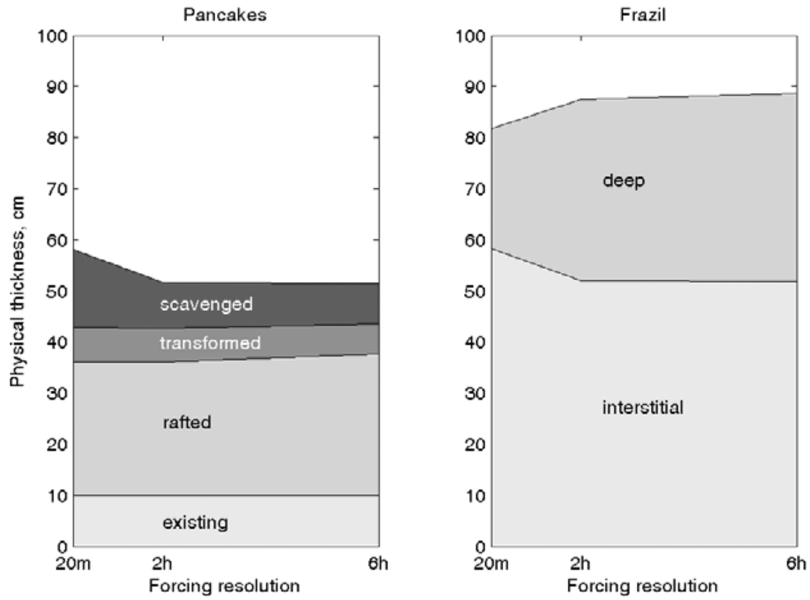

Figure 3. Contributions to final pancake and frazil thicknesses from the various processes and partitions for three resolutions of dynamic forcing. Physical (rather than SIE) thickness is shown. Contributions to pancake thickness come from the existing platforms, rafting from compression of the array, transformed frazil, and scavenged frazil. Total frazil slick thickness is the sum of the interstitial and deep portions. The interstitial frazil thickness is the same as the total pancake thickness since the frazil slick has a greater draft than the pancakes at all resolutions.

the initial frazil area, reducing it to the minimum 10%, with pancake rafting occurring from Day 113, as indicated. No initial frazil conversion to pancakes takes place since the frazil fraction drops below the 35% threshold before it has aged sufficiently. Divergence restores a sufficient frazil fraction to transform after day 116, increasing the pancake area fraction in stages from thereon.

[33] Pancake thickness rises quickly once the initial frazil compression is complete, through a combination of rafting and frazil scavenging. It should be noted that the thicknesses plotted in the bottom graph are averaged over the area occupied by the pancakes. Equivalent thickness therefore drops when thin, new, pancakes are added to that area following conversion from frazil ice.

[34] Total ice volume produced in this scenario is 1.3×10^8 m^3. An analogous congelation ice cover (0.35 open water fraction, 7 cm SIE ice cover over the remaining area) would produce only 6.7×10^7 m^3 of ice under the same forcing, or an equivalent thickness of 29.8 cm SIE, less than 50% of the frazil/pancake ice production.

[35] The frazil/pancake ice production, which occurs purely in the interstitial frazil fraction, is partitioned between the final frazil slick (8.1×10^7 m^3), frazil scavenged onto the pancakes (3.5×10^7 m^3) and frazil transformed into new pancakes (1.6×10^7 m^3). Final pancake thickness is around 40 cm SIE, or 57 cm actual thickness. Scavenging contributes 10.6 cm of this SIE thickness, with rafting being the dominant thickening mechanism at 18.2 cm contribution. This is expected given the sustained compression undergone by the array. New pancakes, transformed from frazil ice contribute less than 5 cm SIE of the final thickness. Final frazil slick thickness exceeds that of the pancakes, with 9.4 cm SIE deep frazil underlying the whole area.

2.2.2. Role of High-Frequency Motion

[36] To examine the effect of the high-frequency motion (observed by the buoys) on ice production, the resolution of the applied positional forcing was varied from the maximum 20-min value. The reduction in dynamic resolution was imposed as a low-pass filter on the buoy motions. The filtered change-in-area was then applied at 20-min intervals, regardless of the dynamic resolution chosen. Meteorological forcing was also applied at 20-min intervals regardless of the resolution chosen, using cubic spline interpolation from the 1-h native interval. This scheme ensured that only differences in the fine-scale motion of the buoys are contrasted since the meteorological forcing remains constant. Figure 3 shows the different contributions to final pancake and frazil thickness, for various resolution dynamics.

[37] The high-resolution (20-min) dynamic forcing has no effect on overall ice production since such forcing only serves to thin and thicken the frazil slick. The major effect of the high-frequency forcing is to increase the volume fraction accounted for by pancakes and reduce the frazil fraction. This arises from increased scavenging of the frazil slick by the pancakes, as demonstrated by almost double the contribution from scavenging at 20-min intervals (10.6 cm) as for 2-h (6.4 cm) or 6-h (5.5 cm) forcing. This is understandable, given the increased path length that the pancakes are subjected to with the high-frequency dynamics. In the current example, the percentage increase in total pancake thickness owing to the high-frequency forcing is

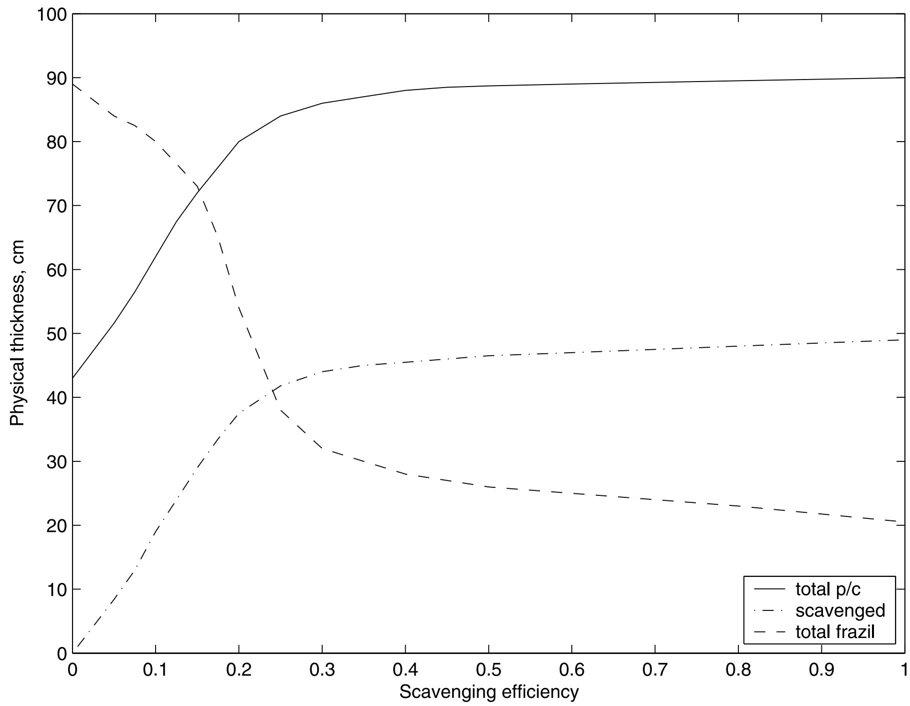

Figure 4. Effect of scavenging efficiency ε on the scavenged and total pancake thickness. Also shown is the total frazil thickness (interstitial plus under-riding). All figures are generated at the full (20-min) resolution forcing and show physical (rather than SIE) thicknesses.

relatively small (12%), but this contribution will rise in less convergence-dominated scenarios, as the rafting component is reduced. Other contributions to pancake thickness (rafting, transformation) remain similar with dynamic resolution, as would be expected from the dominance of large-scale dynamics in these processes.

2.2.3. Scavenging Efficiency Effects

[38] Figure 4 shows the dependence of total pancake thickness, the scavenged contribution and total frazil thickness on scavenging efficiency, ε. Physical thicknesses are shown, as opposed to solid ice equivalents. The point at which frazil slick ceases to be deeper than the pancakes is then given by the crossing point of the two curves ($\varepsilon \cong$ 17%). The scavenging efficiency has a rather linear effect on the contribution of frazil ice until a value of 25%, where the contribution reaches 40 cm physical thickness. The frazil slick thickness drops rapidly over the same interval, resulting in a severely reduced frazil volume for the scavenging to operate upon. Increasing scavenging efficiency beyond this point therefore has a much smaller effect. The "irreducible" frazil thickness of 20 cm with 100% scavenging efficiency results from the divergent period at the end of the simulation: the pancakes do not converge sufficiently to scavenge the ice produced during this cold-air outbreak.

[39] It is interesting to examine how the choice of ε impacts the influence of the high-frequency motion, in terms of the scavenged contribution to pancake thickness. Scavenged layer thicknesses for 20-min and 6-h resolution runs are plotted in Figure 5, together with the difference between them (i.e., the influence of the high-frequency motion). Increasing scavenging efficiency increases the influence of the high-frequency motion until a maximum is reached at around $\varepsilon \cong 17\%$, the same value at which frazil ceases to under-ride the pancakes in the full resolution simulation.

[40] The correspondence demonstrates an emergent property of the model parameterization, which does not consider the deep frazil to participate in the scavenging process. The deep frazil thus acts as a reservoir to replace the interstitial frazil removed by scavenging, enabling the increased scavenging efficiency to directly increase the scavenged volume. Once this reservoir is exhausted, however, continued scavenging will deplete the interstitial frazil thickness, reducing the impact of more efficient frazil removal. The 6-h simulation can then "catch up" with the 20-min results since it takes longer for this reservoir to be depleted in the absence of the high-frequency motion. An ε value of 50% is sufficient for the 6-h forcing to scavenge all the available frazil and build an equivalent layer thickness to that seen in the full resolution simulation.

2.3. Discussion

[41] The simulation results in a frazil slick thickness which is significantly higher than field observations suggest, though the overall volume (and hence equivalent thickness) of the ice cover is in close agreement with field measurements. The very limited number of observations in the Weddell Sea and Odden have never observed the frazil slick to be deeper than the pancakes embedded within it, whereas the model suggests a physical frazil thickness of nearly 82 cm, compared to a physical pancake thickness of 58 cm. The interacting nature of the various processes in the model render it difficult to establish which factor is responsible for this perceived shortcoming since frazil slick thickness may be reduced by any of the following means:

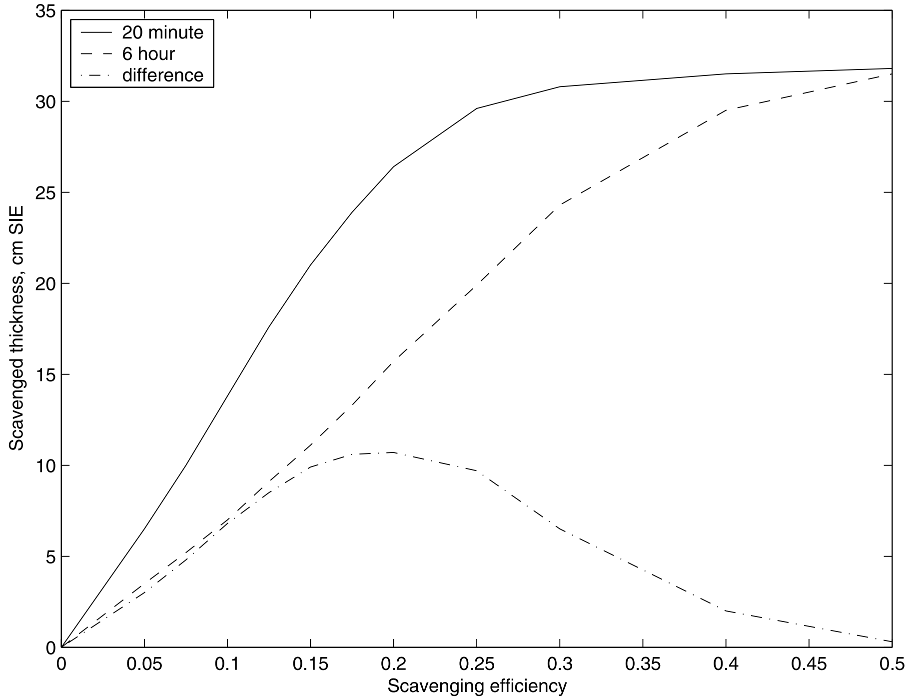

Figure 5. Thickness of the scavenged pancake layer versus scavenging efficiency plotted for 20-min (solid line) and 6-h forcing (dashed line). The difference between the two forcing results is also shown (dash-dotted line). All figures are solid ice equivalents (SIE).

[42] 1. The scavenging efficiency can be increased. The 5% value is based on a modeled frazil thickness at the end of the first cold air outbreak, which may be erroneous. Significant increases in the value of the parameter are required to reduce final frazil thickness to values more in line with field observations, though the model is relatively insensitive for $\varepsilon > 25\%$, at which point frazil thickness is more in line with observed conditions in the field. Such a shift in value for ε, though apparently radical, would only require that the frazil slick thickness at the end of event 1, from which the value was originally derived, was in fact 17 cm instead of the modeled 27 cm, which is quite possible.

[43] 2. The scavenging efficiency may vary with the area fraction of the slick. It can be envisaged that significantly reduced frazil area fractions are more efficiently scavenged onto the surface of the pancakes since a mutual barrier exists to prevent the frazil crystals being pushed aside rather than over the pancakes. This is similar to the formation of pancake rims described in the work of *Pedersen and Coon* [2004], which describes frazil being "pumped over the two converging edges of cakes." No data exist on this process, though it may be tractable to numerical simulation or study in an ice tank.

[44] 3. Significant volumes of frazil may be transformed into pancakes by the bottom accretion method, not parameterized here.

[45] 4. The rate of frazil production may drop as the frazil slick thickens. This is likely to be true if the slick becomes particularly thick, as the buoyancy of the underlying crystals is sufficient to lift the slick surface clear of the water, hence insulating the ocean surface from the overlying cold air. Such surface-drained slicks were observed by the author in the Odden region of the Greenland Sea.

[46] The uncertainly over the scavenging efficiency hampers the assessment of the importance of the high-frequency motion since it directly impacts the one process which varies significantly with this small-scale oscillation. The impact of the process varies significantly over the range $10\% < \varepsilon < 25\%$ and is relatively insensitive at other values.

3. General Discussion

[47] Development of the scavenging/redistribution model has highlighted our limited understanding of the effect of a pancake/frazil ice cover on ocean-atmosphere heat exchange. The model assumes that (1) only the interstitial frazil area contributes to ice production; and (2) the rate is not modified from the "free surface" figure. These two assumptions have opposite effects on the ice production.

[48] Little literature exists to aid our understanding of these processes. Most measurements and theory development have been focused on frazil formed at low area concentrations in relatively small leads or polynyas, which is subsequently herded downwind until it collects against the edge of the lead or polynya and freezes into a solid ice sheet. Important considerations in this application are wind speed and fetch (lead width), which indirectly parameterize the turbulence which both limits frazil production and mixes the frazil crystals down into the water column, determining their volume concentration.

[49] These parameters have little relevance to the vast frazil/pancake fields of the Antarctic: turbulence levels there are largely determined by the high-amplitude swell imping-

ing on the ice cover from the Southern Ocean. Turbulence is thus determined by nonlocal wind forcing (distant storms) and the dimensions of the ice cover (thickness, area concentration, distance) between the measurement site and the open ocean, plus the properties of the waves themselves (amplitude, period). *Pedersen and Coon* [2004] nonetheless presented a nonphysical best fit of *Alam and Curry*'s [1998] wind speed to ice thickness relation for the Odden. This is partly justified since the relatively small scale of the Odden implies a closer proximity to storm wind forcing and a far less significant degree of damping of the resulting ocean waves by the ice cover. They found that an empirical "lead width" of 1.5 km fitted the observed pancake thickness best, though the scatter was considerable.

[50] Conceptually, it seems unlikely that only the interstitial frazil area contributes to ice production: the pancakes are small and highly mobile and it is therefore not unreasonable to assume that the entire area "sees" the cold atmosphere at the integrated timescales over which heat loss from the ocean occurs. Additionally, the pancakes are highly porous, unlike congelation ice, and the water within them is therefore less insulated from the cold air than would be the case under a congelation ice sheet.

[51] An opposite effect is the modification of ocean-atmosphere heat fluxes by the presence of a frazil/pancake ice cover. Turbulent fluxes dominate heat exchange during frazil formation and the various methods of calculating these each use parameters that are modified by an ice cover. Bulk formulae use an exchange coefficient, while Monin-Obukov similarity theory requires a roughness length, which is certainly different from the open water value. Very thick frazil slicks, such as that observed in the Odden, will modify the area-integrated surface temperature from the freezing point of seawater, as will the presence of pancakes, the cooling of whose top surfaces will also account for some fraction of the heat flux which would otherwise contribute to ice formation [*Leonard et al.*, 1998b].

[52] Given the supposed overproduction of the frazil model in the current study, the rate reduction effect may be expected to dominate. This expectation is enhanced by the tank measurements of *Smedsrud* [2001], which determined an ice production rate less than one third of the unmodified production with similar fluxes. A lack of equivalence between tank and field conditions, specifically the relative turbulence and mixing levels, may be responsible for this disparity, however.

[53] Heat flux measurements over a growing pancake-frazil ice cover are required to resolve these problems, relating the measured heat flux to that which would be expected in the absence of the ice cover. The author is not aware of any such field measurements to date, and the unique nature of the ice cover makes the usual measurement methods difficult to apply. Over consolidated pack ice, turbulent heat fluxes are usually measured from meteorological buoys with air temperature and wind speed sensors at two heights (usually 2 and 4 m). The turbulent heat fluxes can then be calculated by Monin-Obukov similarity theory [e.g., *Vihma et al.*, 2002]. Such buoy or ship-based measurements are difficult or impossible in a growing pancake ice field, though aircraft observations, either using towed sondes from helicopters [*Vihma et al.*, 2005] or instrumented fixed-wing aircraft, remain feasible.

[54] Further development of the scavenging model also requires a better-constrained path length traversed by an individual pancake. Centimetric-scale measurements of the separation between adjacent pancakes as waves move past are required to examine compression/rarefaction at the trough/crest of the waves and the down-wave motion. Tank experiments form an obvious first step, though attempts by other investigators have been inconclusive. Field measurements are more difficult to achieve, though video photography from a hovering helicopter is suggested, possibly using marked pancakes (e.g., dye or chalk powder). The partitioning between top-layer growth and bottom or lateral accretion is also crucial to assigning the correct importance to the scavenging process.

4. Conclusions

[55] The study describes the development of a process model for the evolution of the wave-influenced pancake/frazil zone of the Antarctic sea ice cover. A 1-D energy balance model is coupled to a redistribution model whose dynamics are derived from an array of drifting buoys deployed for the purpose. The concept of scavenging (where frazil ice crystals are scooped onto the surface of existing pancakes to freeze in place) is introduced, and a phenomenological parameterization of the scavenging efficiency, on the basis of the path length traversed by a pancake and the surrounding frazil slick thickness, is derived. The scavenging efficiency is then incorporated in a redistribution model which parameterizes other processes unique to the pancake/frazil ice cover, using representative values derived from field observations: The frazil ice slick is allowed to thicken under convergence and under-ride the pancakes; areas of frazil ice are transformed into pancakes if they exceed thresholds of area fraction (0.35) and age (24 h); a maximum hexagonal close packing pancake fraction is maintained (0.90), with pancakes rafting if compression continues past this point. The contribution of each process to the final pancake and frazil thickness is then tracked.

[56] The frazil/pancake ice production was found to be approximately twice what would be expected from a congelation (pack ice) cover with the same initial equivalent thickness, even if that solid ice cover were allowed to undergo the high-frequency divergence oscillations seen only in the unconsolidated ice cover. Such disparity highlights the need to correctly model the early stages of the formation of sea ice in the Antarctic, if one is to adequately describe the input of salt to the ocean and ocean-atmosphere heat fluxes in the region.

[57] High frequency motion significantly affected the partitioning of ice volume between frazil and pancake phases, through increased scavenging of the frazil crystals onto the top surface of the pancakes. The high-frequency motion had maximum effect when the interstitial frazil thickness matched the pancake thickness at the end of the simulation. For the simulated period, this corresponded to a scavenging efficiency, ε, of 17%, at which value the proportion of pancake ice was modified from 61% (6-h forcing) to 79% (20-min forcing) of the total ice

volume. The model did not incorporate any mechanism for enhancing total ice production with high-frequency motion in a frazil/pancake ice cover, however, since the frazil slick was assumed not to modify the sea-air heat flux from the open water value and relaxes to take up any divergent area. Possible sources of the high-frequency forcing (and the possibility of higher divergence values being observed at even shorter sampling intervals) were examined in DW06, concluding that waves, either surface or internal, were the likely causes, though higher-frequency field measurements are necessary to unequivocally attribute the motion.

[58] Rafting was shown to be the dominant mechanism for thickening the young ice cover, resulting from the dominantly compressive forcing seen in this case study. Such compression is far from unusual since high winds are associated with low-pressure systems traveling from west to east across the region: the leading edge of the low brings northerly winds which are able to advect the thin, unconsolidated, pancakes southward without significant internal stress opposing the motion. Analysis of ice cores indicates that such rafting is extremely common in the field [*Lange et al.*, 1989; *Lange and Eicken*, 1991; *Dai et al.*, 2004], with the rafting occurring from the earliest stages of development and having layer thicknesses of approximately 10–12 cm [*Jeffries et al.*, 1994; *Worby et al.*, 1996]. *Dai et al.* [2004] suggested that wave-induced rafting was the dominant mechanism for the observed layered structure, but the author's field observations conducted using a camera-equipped ROV at four sites in the region saw little evidence of rafting in young pancakes outside the area influenced by the passage of the ship, even in the presence of a 2–4 m amplitude swell. It is suggested that on the scale of the waves, there is a lack of anything "to push against" to achieve rafting (since the pancakes tend to move in phase) and it requires large-scale compression, as seen in the current study, to bring this about.

[59] The scavenging/redistribution model represents a first attempt at realistically simulating the timing and partitioning of ice production in the period before consolidation. It reproduces the 60 cm thick ice cover suggested by earlier field observations [*Wadhams et al.*, 1987], though several empirical factors are used, the model was not "tuned" to achieve this result. The model gives considerable insight into the processes involved, though it pushes the existing data to the limits of their applicability. Its usefulness lies in defining the questions that need to be asked to improve understanding of the process, which center on (1) understanding the effect of the two phase ice cover on ocean-atmosphere heat exchange; and (2) placing the phenomenological parameterization of scavenging efficiency into a more physically justified framework.

[60] A full simulation of the growth to consolidation of the frazil/pancake ice cover should include wave forcing since it is the waves' amplitude and period which determine whether congelation or pancake/frazil ice are grown. In the current study, the timing of consolidation is known from buoy data. The ECMWF wave model (WAM) has been shown to be in good agreement with wave data from the buoys at the ice edge (M. J. Doble, unpublished data, 2000) and can be used operationally as input from the open ocean. Models which parameterize the pancake/frazil mixture as a viscous layer have begun to show good agreement with field observations of wave attenuation in the region [*De Carolis and Desiderio*, 2002], and a coupled thickness-attenuation model can be envisaged. Once the ice cover is determined to have consolidated, the usual pack-ice thermodynamics models can be applied.

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